

Anonymous Referee #2

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This is a very interesting article that gives a quantification of errors induced by the interpolation methods. The paper is nicely written, but I would like to have more description of the ALT interpolation method, as it is the one used for the final tests. The time units should be uniformed (ka in figures and kyr in the text and captions). I encourage the authors to consider the following comments and recommend publication after minor revisions.

Comments:

P66 L26: GICC05 chronology should be cited with full references: Vinther et al., 2006, Rasmussen et al., 2006, Andersen et al., 2006 and Svensson et al., 2008.

Done

P67 L25: it is not really how Datice works. I propose to replace "among all timescales" by "among initial timescales and age constraints by taking into account their respective confidence intervals".

Done

P67 L26: replace Talos Dome by TALDICE and add NGRIP. The references for the TALDICE-1a age scale are Buiron et al., 2011 and Schüpbach et al., 2011, not Stenni et al., 2011.

Done

P68 first paragraph: please add a few sentences on the origin of ALT and why you tested this method.

We added these sentences:

ALT was developed as a complement to ACCUM for situations where the layer thinning is not well constrained by ice-flow modeling. It was inspired by annual layer interpretations when the best choice for an uncertain year is the one that matches the average annual layer thickness best.

P69 L2-4: your definition of the tie points is not clear. Are they taken on the gas or ice age scale? From the chronology file I see that it is the ice age corresponding to the depth in the table, but it is confusing due to the intervention of methane in your explanation.

We have changed the wording to make it clear that while we choose ages guided by times of significant methane variations, the tie points are ice-ages.

We use WDC06A-7 as the "true" timescale. Eleven ice-age tie points (Table 1) are used to evaluate three interpolation schemes by interpolating between these tie points and comparing results with the "true" timescale. We use tie points similar to what has been used in other Antarctic timescales (e.g. ages of identifiable variations in methane) except during the mid and late Holocene when they are evenly spaced (2, 4, and 6 kyr).

P69 L27: the Bayesian approach allows the thinning, but also the accumulation rate and the lock-in depth to vary.

This has been changed, as also suggested by the first reviewer:

The Bayesian statistical approach (Lemieux-Dudon et al., 2010; Veres et al., 2013; Bazin et al., 2013) allows the thinning function, accumulation rate, and lock-in depth to vary within a tolerance to better reconcile the age of tie points with the initial modeled timescale.

P70 L1-3: it is possible to use Datice with only one site considered. It will only consider the absolute age markers and the initial guess of accumulation, thinning function and lock-in depth to obtain a new

chronology. This is what has been done for the TALDICE-1a chronology (Buiron et al., 2011, Schüpbach et al., 2011).

The paragraph has been revised to:

Ice-flow models forced by accumulation rates inferred from stable isotopes do not exactly match tie points (Ruth et al., 2007; Parrenin et al., 2007) and are commonly adjusted to better match the depth of age markers (e.g. Dreyfus et al., 2007). The Bayesian statistical approach, known as DATICE, (Lemieux-Dudon et al., 2010; Veres et al., 2013; Bazin et al., 2013) allows the thinning function, accumulation rate, and lock-in depth to vary within a tolerance to better reconcile the age of tie points with the initial modeled timescale. We compare ALT with three different published timescales for EDML and discuss the consistency of the interpolations in a later section.

P74 L22-24: “the other interpolation methods overestimate the age because they yield smaller layer thicknesses at the older side of the interval” For me, the figure shows that the ages are underestimated, as the difference (WDC06A-7 – interpolation) is positive between 8-12 ka. Please check consistency between text and figures.

Corrected

P75 L25-2: “if the age difference 500 yr from the closest tie-point is 50 yr”. This is not very clear. You should reformulate this example or keep only the next sentence that is more understandable for the rate of accumulating uncertainty.

We have rewritten the section to be clear:

We use the age differences to estimate the rate at which different interpolation methods accumulate age uncertainty and calculate the rate of accumulating uncertainty as the absolute value of the age difference divided by years from closest tie point. For instance, if the age difference is 50 years at a point 500 years from the closest tie point, then the uncertainty has accumulated at a rate of 10 years per hundred years. This is done for all of the ages between 2 and 29.6 kyr.

P76: 1 sigma corresponds to 68%, not 67%. In Figure 5 caption you wrote 66%. Check consistency.

Corrected

P77 L28: you wrote 200 yrs in the text, but it is 181 yrs in the Table. You should write 181 yrs also in the text for consistency.

Corrected

P78 L9: the EDML1 timescale was published by Ruth et al., 2007, not Parrenin et al., 2007.

Corrected

comment: the depth-age of tie-points for the test on WAIS are not directly consistent with the depth-age of tie-points in the EDML test. I mean that for WAIS you took ice ages that correspond to ages of methane events. For EDML you used the ice age at the same depth of methane events. To be consistent between your tests, you should have taken the EDML depth for ice ages equal to ages of methane events.

There is no way to make the tie point choices perfectly consistent. For WAIS Divide, the timescale was not developed using tie points, so we could choose any tie points we wanted. While we debated

choosing tie point ages for WAIS that included the delta-age values (i.e. the depth of the methane variation), we ultimately felt this was unnecessarily confusing since we were not discussing the WAIS methane record. For EDML, we felt the ice age at the depth of the methane variations was the most reasonable choice. For Law, Byrd and Siple, we identified the ice-age tie points by looking at abrupt changes in the annual layer thickness which, similar to EDML, tended to be at the depths of methane variations.

P78 L15-16: maybe add that this feature was also observed on the WDC06A-7 layer thickness at nearly the same time.

The abrupt accumulation increase at WAIS occurs during stable isotope values, while at EDML the thick layers are a consequence of assuming a relationship with the stable isotopes. Whether EDML shows an abrupt accumulation as observed at WAIS Divide is not known, although this may be answered by the ongoing annual layer interpretation for EDML.

P78 L21-22: "Overall, the variation in annual-layer thickness between ALT and AICC2012 is about the same as among the three EDML timescales". Please explain more precisely.

We have reworded this paragraph. We calculated the differences in layer thicknesses between the timescales and the mean and standard deviations of the differences are smallest for AICC2012-ALT. We do not include this calculation in the text because we feel it is more detail than necessary for the simple point that the ALT interpolation is reasonable for EDML.

Annual-layer thickness profiles from the EDML1 and LD2010 timescales are also shown in Figure 6A. These two timescales use the same abrupt methane variations as AICC2012 for ages older than 11.5 kyr (ice age), but ages younger in AICC2012 are based on volcanic sulfur matches with the North Greenland ice core and annual layer counting (Veres et al., 2013). The inferred layer thicknesses using ALT are, on average, more similar to those of AICC2012 than are the annual layer thicknesses of either EDML1 or LD2010 to AICC2012. EDML1 predicts thicker layers at both Antarctic Isotope Maximums 0 (~12 ka) and 1 (~15 ka). LD2010 predicts a 25% increase in annual layer thickness between 8 and 7.2 kyr when the other timescales show little change. The smoothness requirement causes ALT to miss high-frequency structure in layer-thickness profiles, but that requirement also avoids creating large variations in annual layer thickness that may not be real. That the differences in layer thickness among the three EDML are larger than the differences between ALT and AICC2012 indicate ALT is a reasonable interpolation for EDML.

P78 L27-28: did you test ALT with ages deduced from EDML1 or LD2010, to see if it reproduces the same behaviour after 10 ka and at 15 ka? I would like to see these results.

We did apply ALT to the other EDML timescales. The main difference between the different ALT interpolations is that annual layer thickness variations in the original timescales is reflected in the ALT interpolation. Overall, the ALT AICC2012, like the AICC2012, is the smoothest of the three. The behavior of the three interpolation is qualitatively similar. ALT predicts thicker layers at 10 ka than the original timescales while predicting thinner layers at 12 ka – because ALT has no knowledge of the d18O high at 12 ka. At 15 ka, all three ALT interpolations predict an annual-layer thickness maximum, whose timing and magnitude depends on the original timescale. See Figure at the end of this response.

P80 L6: which interpolation step?

We don't understand this question.

P80 I21-25: ages are different than the ones given in Table 4. Please correct this. Moreover, there is the same time span in-between tie-points at Law Dome and Siple Dome / Byrd, so it cannot be the main cause for a larger difference.

Age of the Law Dome tie points (19.5 ka) has been corrected. We have rephrased this paragraph: ALT annual-layer thickness profiles are shown in red in Figs. 7A, C, E. Age differences between the original near-linear interpolations and ALT are shown in black. All three timescales show significant age differences. The largest differences are in the Siple Dome timescale; ages shift by as much as 1200 yr around 20 kyr, which is within the estimated 2000 yr uncertainty for the timing of the abrupt isotope change ~22 kyr (Brook et al., 2005). For Byrd, age differences are up to 1000 yr at about 24 kyr. At both Siple Dome and Byrd, changes in the timescales more recent than 18 kyr are less than 200 years. At Law Dome, the timescale ends at 21 kyr. There is no tie point at the onset of the deglacial rise (~18 kyr), which results in a relatively long span, 16.2 to 19.5 kyr, when annual-layer thickness decreases by a factor of 2 between the tie points. The result is a large age discrepancy of over 500 years centered at 18.1 kyr. As shown with the WDC06A-7 timescale, linear or near-linear interpolation performs poorly when the annual-layer thicknesses change significantly between tie points.

P81 L1-2: I suggest to include a comparative figure of water isotopes of WAIS, EDML and Byrd in the appendix to illustrate this point.

We have included this as a figure in this response. The ALT interpolation compresses AIM2 in the Byrd record by eliminating the 3-fold drop in layer thickness during this period (Figure 7A). The character of AIM2 becomes more similar to WAIS Divide and EDML. However, the age of AIM2 remains older. We chose the center point of the thin layers (approximately the dip in d18O during AIM2) as a tie point and thus the age of the middle of AIM2 did not change. We did not address the absolute age because it requires shifting the age of tie points, which was not part of the analysis in this paper. This is why we do not include it as a figure in the final paper.

P81 L4: “shifted up to 150 yr”, younger?  
Younger. Added in text.

P81 L7: “250 yr at 17.5 kyr”, -250?  
Added younger.

P81-82: twice “occurs” in the same sentence.  
Reworded.

Appendix B:

P85 L10-18: I don't understand this paragraph, the B3 terms are not the ones associated with the ALT method? In that case ALT and ACCUM are reversed in lines 11 and 13. If I am not correct, this paragraph is not clear and should be revised.

We have revised the opening paragraph to clear that we use values from ACCUM because ALT does not calculate all of the values needed:

The thickness of an annual layer of age  $A$ ,  $\lambda(A)$ , is related to its thickness when it was deposited (the accumulation rate at that time),  $b(A)$ , by the thinning function,  $\Lambda(A)$

$$\lambda(A) = \Lambda(A)b(A) \tag{B1}$$

ACCUM minimizes the second derivative of the accumulation rate:

$$\frac{\partial^2 \dot{b}(A)}{\partial A^2} \quad (\text{B2})$$

ALT minimizes the second derivative of the annual-layer thickness:

$$\frac{\partial^2 \lambda(A)}{\partial A^2} \quad (\text{B3})$$

B3 can be rewritten after substituting in B1

$$\frac{\partial^2 \lambda(A)}{\partial A^2} = \frac{\partial^2 \Lambda(A)}{\partial A^2} \dot{b}(A) + 2 \frac{\partial \Lambda(A)}{\partial A} \frac{\partial \dot{b}(A)}{\partial A} + \Lambda(A) \frac{\partial^2 \dot{b}(A)}{\partial A^2} \quad (\text{B4})$$

Unfortunately, ALT does not compute a thinning function or an accumulation history needed to evaluate the three terms on the right hand side of B4. However, ACCUM does calculate all of these terms and we can use these to better understand how the ALT minimization differs from the ACCUM minimization. Figure A1 shows relative values for the three terms on the right hand side of Eq. (B4) evaluated for ACCUM as a function of age on the WDC06A-7 timescale.

P86 L9: replace “first” by “third”, and I am not sure “deemphasizes” is proper English.

Corrected.

Tables and figures:

Table 1: precise that ages come from WDC06A-7 age scale. Moreover, check consistency between these points and the ones used for your tests. On the figures the lines do not necessarily correspond (obvious for the tie-point at 14 ka)

The table values have been corrected

Table 2: Average age bias

Added

Table 3: missing units and the age scale from which the tie-points originate. You must precise that these ages are from AICC2012 and not from the other two EDML chronologies. You should also precise the uncertainty of the original chronology at these tie-points.

We have added the units and that they are from AICC2012. We do not include the uncertainties in the tie points because we discuss only interpolation uncertainties.

Table 4: missing units and “depth” and “ice age” lines of Low Dome are inverted.

Corrected

Figure 1: standardisation of ka and kyr. You know that this can be updated with data on AICC2012 as NGRIP is part of it (available on Pangaea and ncdc databases).

We did not know the methane data on the AICC2012 was available online. We chose not to show both methane records on AICC2012 because we want to illustrate how an Antarctic timescale is tied to a Greenland timescale and felt having them already on the same time scale created confusion.

Figure 5: 1 sigma is 68%, and not 67 or 66%.

Corrected

Figure 7: precise the age difference. I suppose it is the age scale – ALT?

That the age differences are plotted on the original timescale has been added to the caption.

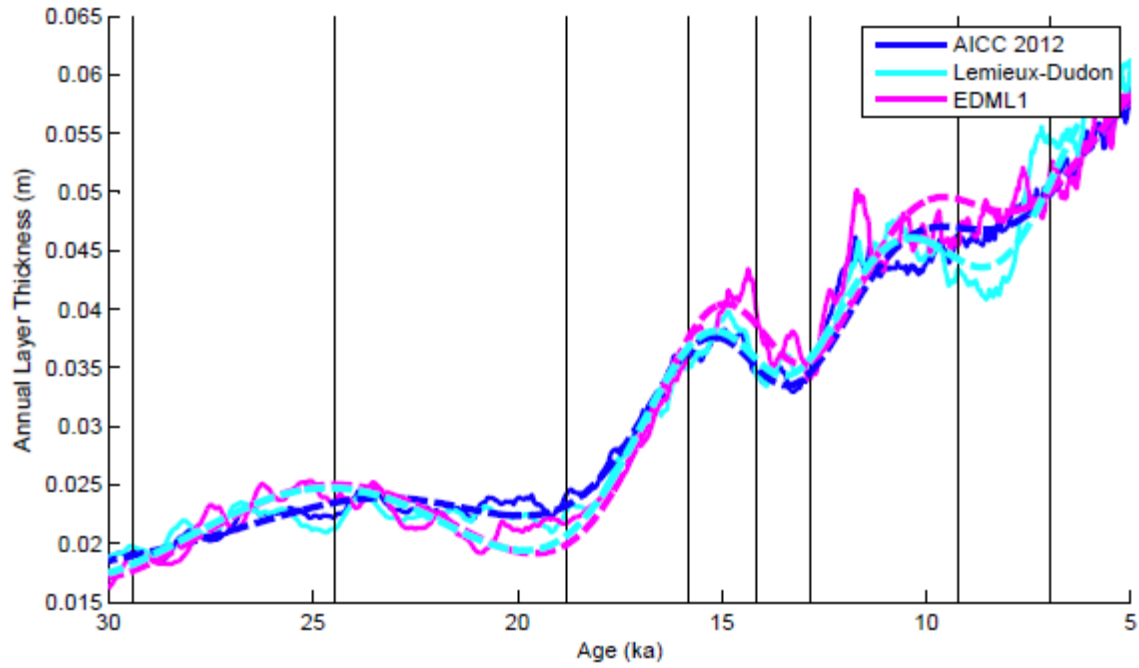
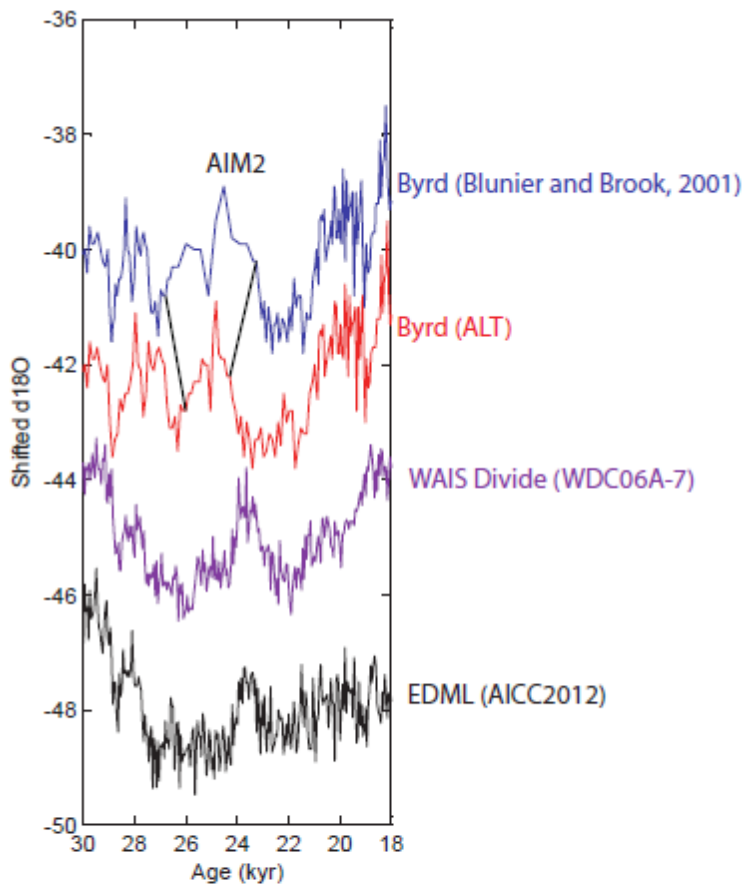


Figure: Annual layer thicknesses for the three EDML timescales (solid) and ALT interpolations based on those timescales (dashed). The same depths of methane variations were used in the ALT interpolations for each timescale (but the ice age for those depths varies for each timescale). The black vertical lines are the ice-age tie points for AICC2012.



The ALT interpolation compresses AIM2 in the Byrd record making it more similar in character to AIM2 in WAIS Divide and EDML. The timing of AIM2 in Byrd is still older because the midpoint of the event (dip in center of event) was chosen as a tie point.