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General Remarks

This paper uses the opportunity provided by the annually resolved WAIS Divide (WDC06A-7) timescale to test the performance of three interpolation schemes on the fidelity of the timescale between eleven tie points. The authors confirm the unsurprising, and previously established (Waddington et al., 2003) result that linear interpolation of ages between ties leads to biases, and errors which are larger than more sophisticated methods with higher-order, smooth interpolants. The paper is able to quantify the relative performance of the various methods using the WDC06A-7 timescale, and also presents some discussion and analysis around the implications of interpolations used for Byrd, Siple Dome and Law Dome deglacial records. As a methodological paper this makes a valuable contribution, highlighting an important issue for constructing ice core chronologies. It also highlights the need to consider interpolation errors when interpreting features in records. The paper does contain some small errors which require fixing and one or two analytical questions which arise. More importantly there are several instances where the interpretations made or language employed might be misleading to the reader, especially around the definition of when an interpolation method is linear or not, and the application of WAIS specific values to other records. I would recommend this paper is suitable for publication once these matters have been addressed.

Comments and corrections

Overall remark on the characterisation of 'linear interpolation'

A key point made by this paper is that linear interpolation of ages between tie points should be avoided and I agree. This paper mis-characterises the Law Dome timescale methodology as being a "variation of linear interpolation" (p67 line 20), although later (p80, line 3) acknowledges that it incorporates a Dansgaard-Johnsen flow relation. It should be clarified in the earlier instance (p67) that the method used is intrinsically non-linear (accounting as it does for flow thinning), but shares some of the biases and problems associated with simple linear interpolation because it has constant accumulation steps between tie points. It is true that the non-linear effect of flow thinning becomes small over short intervals or toward the bed, and that the 'stepped' accumulation leads to a stepped annual layer thickness as seen in Figure 7E. While this leads to the same type of errors seen in simple linear interpolation (with 'flat steps') it can also be seen in figure 7E that the annual layer thickness of the original Law Dome scale and the ALT scale are close across several tie intervals (see, e.g. 14.8-16.2 ky) and certainly generate smaller magnitude biases than 'flat steps' (without thinning) would do. This is also relevant when applying the WAIS-derived uncertainty-rate accumulation to Law Dome (see below).

The introduction has been rewritten to more accurately characterize the Law Dome timescale:

Law Dome (Pedro et al., 2011) does not use linear interpolation, instead assuming constant accumulation rates between tie points and a thinning function computed with a one-dimensional ice-flow model. The resulting timescale, however, has many of the same features as a timescale constructed with linear interpolation, as is shown below.

We discuss the impact on uncertainties and biases in response to specific comments below.

Other points

P66 line 9 "...abrupt changes in inferred duration [of depth intervals] at tie points..."

We reworded the sentence as:

Linear interpolation yields large age errors (up to 380 yr) between tie points, abrupt changes in duration of climate events at tie points, and an age bias.

P67 line 17 “Two common approaches [have been used]...” suits the tense of following sentence better.
Corrected

P67 lines 20 and following “variations of linear interpolation were used”... As noted above, some clarification would be appropriate re Law Dome.
See response above to opening comment.

P77 line 13 “... and a carbon dioxide record measured in a single core...” should read...”and carbon dioxide records measured from individual cores” Since the Pedro et al study used two CO2 records, not one
Changed

P77 line 28 “...result in ages biased 200 yr too old [at WAIS] for linear interpolation” This is not a general result
We have changed the sentence to read:
For instance, the increasing annual-layer thicknesses of the deglacial transition (21 to 12 kyr) result in ages biased 181 years too old for linear interpolation compared to WDC06A-7.

P78 lines 2-5 This comparison between the Pedro et al CO2 lag and the 200-yr WAIS interpolation bias implies that the lag reported in Pedro may be too large by a similar amount. This implication is not founded and overlooks the following:
We did not intend to imply anything specific about the lag reported in Pedro et al. 2012; only that the interpolation uncertainty and potential bias is large enough to affect such analyses. We agree with the reviewer that the timing of this discussion could be improved since we had not yet shown that Byrd, Siple Dome, and Law Dome timescales have many of the features of linearly interpolated timescales. Therefore, we removed the discussion of Pedro et al. 2012 from this paragraph and have instead inserted a new paragraph into the “Application to Byrd, Siple Dome, and Law Dome section”. In this new paragraph, we discuss that the gas timescales are also affected and that the effect on the lag correlation is uncertain.

Both Reviewer 1 and 3 in their comments about the effect on the Pedro et al. (2012) lag forget to include that the Byrd and Siple Dome gas timescales would also be affected. This means that for either the lag with Byrd CO2 or with Siple CO2, 4 of the 6 timescales involved are affected. While it is tempting to assume that the biases would largely cancel, that will not necessarily occur depending on which ages for each timescale are affected and what the d18O and CO2 variations are at the affected times. In the new paragraph, we are explicit that the effect on the lag correlation is unclear:

The magnitude of the linear interpolation biases are similar to the magnitude of the century-scale lead (-56 to 381 yr) of Antarctic temperature to carbon dioxide found by Pedro et al. (2012) and suggest interpolation biases have the potential to affect the details of such analyses. Whether there is any significant impact on the Pedro et al. (2012) conclusion is unclear because timescales for both the ice (Antarctic temperature) and gas (carbon dioxide) were constructed with near-linear interpolation: Byrd, Siple Dome, and Law Dome are three of the five $\delta^{18}O$ records in the Antarctic temperature stack and the two gas timescales for carbon dioxide are Byrd and Siple Dome. Redoing the lag analysis is beyond the scope of this paper, but the potential biases indicate future investigations of century-scale leads and lags should include interpolation uncertainties.

Because both the ice and gas timescales in the Pedro et al. 2012 analysis are affected, reviewer 1's comment that "this will reduce the AT-CO2 phase lag inferred by Pedro et al. (2012), and make it in better agreement with the near-zero phase lag inferred by Parrenin et al. (2013)" does not consider the full effect. The effects of changing 5 of the 7 timescales in the analysis (Law Dome ice, Byrd ice, Siple Dome ice, Byrd gas, Siple Dome gas) cannot be easily predicted. To fully understand the effect on the lag calculation will require redoing the calculations with the ALT timescales. Or better yet, applying a Monte-Carlo style analysis with appropriate interpolation uncertainties included. This is beyond the scope of this paper. Joel Pedro and I have discussed doing this in future work.

1) The 200 year bias is a WAIS-specific value and not the correct value for the cores used in the Pedro stack. That is for Byrd, Law Dome, EDML, Taldice or Siple Dome. The interpolation bias estimates for Byrd (30 years) and Law Dome (150 years) are smaller than WAIS, while EDML and Taldice use the Bayesian technique which this paper (P79, lines1-4) suggests is unbiased.
The 200 yr bias (now written as 181) is WAIS specific. As discussed above, the Pedro et al. (2012) analysis is not discussed in the manuscript until the Byrd, Siple Dome, and Law Dome potential biases have been introduced.

2) Taking Siple Dome, which has the largest potential interpolation bias (older 240 years) as an indicator, one would expect that removing it from the Pedro lag calculation would make the stack younger and therefore reduce the lag. In fact, removal (done by Pedro et al in jackknifing tests) of Siple increases the lag by 55 years. This is a powerful indicator that simple expectations in the presence of multiple interacting factors (like the fact that both the CO2 and temperature timescales suffer bias) can be misleading.
The jack-knifing tests do not consider the gas timescales which might be expected to have the larger effect on the lag correlation. That removing Siple Dome increases the lag shows that caution should be taken in trying to extrapolate potential biases of individual timescales to the lead-lag values. The d18O values, not just timescales, influence the lag correlation. These points are now made in the new paragraph as discussed above.

3) The Pedro et al results are computed with a Monte Carlo style sensitivity in which the timespan of comparison was truncated over a 1200yr range of ages from 18.2ky-19.4ky. The results therefore include a substantial portion of the interval of greatest putative bias (Fig 7E) without displaying any inconsistency. Further, this method is likely to have captured in the distribution of lags an allowance for bias variations in this interval.
I discussed this point with Joel Pedro and we decided that with both the ice and gas timescales being affected, we are not sure what effect is expected from varying the range of ages of the analysis. The Pedro et al. (2012) analysis finds the average lag over the entire deglacial period, not just at the onset, so is not acutely sensitive to changes in the timescale at ~18 ka.

As an additional point, the lag estimate in Pedro et al is -56 to 381 years, not 0-400 years. A suggested rephrasing of this section which addresses this might read: "Understanding the potential interpolation biases in ice core timescales is important when comparing phase relationships between records. For example, the study of Pedro et al., compared a composite temperature proxy with two CO2 records and identified a lead of Antarctic temperature with respect to carbon dioxide of -56 to 381 years. It might be expected that interpolation biases in the temperature proxy, when removed would lead to a reduced lag, however jackknife sensitivity tests in Pedro et al, suggest that the effect is likely to be small in this case".

We have changed the lag estimate values. We have not included the suggested language because of the importance of the gas timescales, as discussed above.

P80 line 23 19.5 kyr not 19.1 kyr
Corrected

P80 line 24 19.5ky not 19.2 kyr
Corrected

P80 line 25 ...over 500 yr.... this raises an interesting point about figure 7E which I don't understand. If I'm correct, the quasi-parabolic age difference curves in Figure 7A, C, E are integrations of the difference between the ALT and original timescales from start to finish of the interval. ALT starts a typical interval at higher layer thickness than the original, so as discussed in the manuscript, the errors start accumulating with the original scales running 'old' relative to ALT. When the point is reached where ALT crosses through original, the scales run instantaneously at the same rate, and we see the maximum in the 'parabola'. Why then, does the maximum near 17.7ky in figure 7E not appear to align with the crossover?
The maximum age difference and the cross-over in layer thickness do not align because of the different age scales (the original and ALT). When the layer thicknesses and age differences are plotted by depth, the maximum age difference matches the cross-over in layer thickness.

P81 Section 4.2 This specific example is in some respects of limited value as it is an example built on the comparison of a timescale developed according to the arbitrary assumption of "smoothness" with a separate timescale built on the assumption that accumulation rate over the interval is constant. While the rest of the paper makes the case that the ALT method is generally superior to the abrupt jumps, and I have no quibble with that as a general principle, it is hard to claim that the ALT timescale is preferable to other methods for a given interval in a specific record. Indeed, the authors are careful to avoid this claim (p81 line 17).
This example was chosen to emphasize the importance of including the interpolation uncertainty. Pedro et al. (2011) assign a 320 yr uncertainty to the onset of deglaciation in the Law Dome d18O record. At this climate feature, the interpolation uncertainty substantially exceeds the stated uncertainty. Indeed, the timing of this feature is shifted by 550 years with the only change being the interpolation method.

The Pedro et al. (2011) paper focuses on the phasing of Antarctic and Greenland climate during the Bolling Allerod warming and Antarctic Cold Reversal time periods, and not the onset of deglaciation. The BA warming and the ACR have closely spaced tie points, so the timing inferred by Pedro et al. (2011) is minimally affected by different interpolation schemes.

Putting this aside, if there is to be this discussion, it is not clear that the rate of accumulating uncertainty can be validly transferred from WAIS to Law Dome as they do here. They use the value of 31 yr per hundred yr, which for WAIS, never minding that it is an entirely different site, was based on using the square-stepped annual layer relationship of a naive linear interpolation without flow correction. Since the Law Dome interpolation includes flow thinning, as seen in the 'sloping' steps of Figure 7E, it might be expected that uncertainty would accumulate more slowly – at the very least, the author assumption is not demonstrated: viz that 31yr per hundred is sensible.
The Law Dome timescale results in a decrease in layer thickness from 1.59 mm to 0.75 mm across the 16.2kyr tie point. A linear interpolation jumps from 1.62 mm to 0.74 mm. Thus, the step-change in the

Law Dome timescale is only ~5% smaller than linear interpolation. Including flow thinning with the Law Dome method has a negligible impact on the resulting timescale at this tie point. We therefore used the accumulating uncertainty for linear interpolations. It should also be noted that the 550 year age difference between ALT and the original Law Dome timescale is about the same as the accumulated uncertainty using the linear value of 31 yr per hundred (510 yr uuncertainty), suggesting that the linear value gives an uncertainty in the correct ballpark.

We did not discuss the slight difference between the original Law Dome timescale and linear interpolation because we did not wish to beleaguer a discussion of uncertainties that has larger unknowns (i.e. the change in distance to the closest tie points) and is already well stated that the uncertainties are approximate: "This reinforces that the uncertainties are estimates and should not be interpreted as a precise quantification of the total age uncertainty."

P84 line 3 –J and m symbols should be bold
We will make sure that these appear bold in the final paper.

Table 4 The values and row headings are not correctly placed: the Ice age values and depths are transposed
Corrected

The Ice Age values have been computed from publicly available depth age data and are generally correct with a couple of typos. I do wonder at the rounding of the ages to the nearest 100 years, as this could affect the calculation of accumulated bias over the intervals – this is probably a small effect, and not critical.
Typos: "12.8" kyr age should be 14.8; "12"kyr age should be 21, and units on the rows would be good (kyr and m).
We have added another decimal place for the Law Dome ages and corrected the typos.