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Climate of the Past Discussions

Interactive comment on "An optimized multi-proxy, multi-site Antarctic ice and gas orbital chronology (AICC2012): 120–800 ka" *by* L. Bazin et al.

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"My first question is how the uncertainty is less than 4 ka throughout this entire period even though all of the age markers have a 6 ka uncertainty?"

=> The age uncertainty decreases as sigma/sqrt(N) when N is the number of markers. Thus, it decreases with increasing density of age markers. This explains why the chronology uncertainty is smaller than 4 ka over a period with age markers of 6 ka uncertainties. We have added this explanation in the SOM.

"Are the uncertainties of each of the d18Oatm age markers being treated as independent from each other? If so, is this a valid assumption? I wonder if the uncertainties might be systematic - if the age marker at 749 ka is too young by 6 ka because the

assumed orbital relationship is off, might the 758 ka point be similarly 6 ka too young?"

=> The uncertainty of each δ18Oatm markers is indeed treated independently from each other. The 6 ka uncertainty includes the non-constant precession – δ18Oatm lag error that probably varies with climate as also pointed out by J. Severinghaus and the 2nd reviewer. For old ages, the δ18Oatm ages are consistent with the 10Be ages obtained at the B-M reversal indicating that we didn't miss any precession cycle. Nevertheless, we can't exclude error compensation. In the future, we will be able to implement markers of age difference, which will be more appropriate for δ18Oatm /precession constraints.

"On a different note, I also wonder what effect the background scenario has on determining the uncertainty. I'm unclear on what background scenario was used – whether flow-modeling only or corrected with d18Oatm measurements (Parrenin et al., 2007a,b; Dreyfus et al., 2007). But given the large adjustments to the thinning function between those two possible background scenarios, it seems like the background scenario is quite uncertain."

=> The influence of the background scenario on the final uncertainty is parameterized with its variance, as defined in the SOM. The thinning function used as background for EDC is the one calculated by flow modelling only (Parrenin et al., 2007a). We did not use the one corrected with δ18Oatm otherwise we would not have respected the hypothesis of non-correlation between data and background. The variance associated with the thinning function increases with depth as well as over Terminations in order to reflect possible change in fabrics or dust load that may influence the ice flow (Figure 2). The variance (sigma) at 2783 m, where large corrections on the thinning function have been proposed from the δ18Oatm constraints (Parrenin et al., 2007b), already reaches a value of 0.54.

"My second question is why the gas-age uncertainty is larger than the ice-age uncertainty during this period. I believe d18Oatm is a gas-age marker (unlike dO2/N2 which is an ice age marker even though it is preserved in the gas). Shouldn't the ice-age uncertainty be equal to the gas-age uncertainty plus an uncertainty for the delta-age?"

=> We agree that this presentation of the uncertainty was not logical and it will be changed in the revised manuscript. This was coherent for ice stratigraphic links, but not for the gas stratigraphic links. The reason why the gas age uncertainty is always greater than the ice age uncertainty came from the method we used to calculate the different ages. Datice first calculates the ice age from the background parameters and age markers at depth z, and then it deduces the gas age as being equal to the ice age at the depth z minus Δdepth. Gas age (z) = ice age (z-Δdepth)

As a result, the error on the gas age was defined as the error on the ice age plus an error on the Δdepth. This was not a correct way to calculate the error when the stratigraphic links are provided on the gas phase (in this case, the gas age uncertainty should be smaller than the ice age uncertainty).

In the current methodology, it will be better to improve the expression of the age uncertainty (maximum uncertainty on the ice phase when we are around gas stratigraphic markers and maximum uncertainty on the gas phase when we are around ice stratigraphic markers). We therefore propose to simply express the uncertainty for each depth as the maximum between gas and ice uncertainty. The two uncertainties are really close, with differences of only a few centuries.

"My third question is if the dO2/N2 markers with age uncertainties of 6ka need to be excluded, why is the total uncertainty not increased? Isn't this an indication that the uncertainties of the age markers are not properly characterized? The authors suggest that this is because of the low eccentricity, but doesn't this at least add uncertainty. I am also curious why the uncertainties between 720 and 790 ka are smaller than between 360 and 400 ka when there are other age markers in both the EDC and Vostok cores. Shouldn't the greater density of measurements lead to smaller uncertainty?"

=> The uncertainty is always increased when removing tie-points. Still, the uncertainty

does not increase much with the removal of the two δO2/N2 markers with 6 ka uncertainties when there is the presence of other age markers between 760-800 ka (4 δ18Oatm age markers with 6 ka uncertainty and 2 10Be ice age markers with 10 ka uncertainty). Note that in the revised version, we have decided to keep the δO2/N2 markers with 6 ka uncertainty on the bottom part of the EDC ice core since they were not so much in disagreement with δ18Oatm and 10Be tie-points. Then, the reason why the age uncertainty on the EDC ice core between 720-790 ka is smaller than between 360-400 ka is simply due to the presence of more markers on the EDC ice core. Before 350 ka, there are no stratigraphic links between Vostok and EDC, so that even if numerous markers are available on the Vostok ice core, they cannot be taken into account in the EDC chronology and its associated uncertainty. We feel that this comment may be useful for the reader and we have added a few sentences in the SOM when describing the curve for uncertainties in the chronology.

"I have little intuition for how the uncertainty values are being determined when multiple cores and multiple types of age markers are combined. Because I do not understand the uncertainty values in the deep EDC case where there are not complicated interactions, I am skeptical of the uncertainty values for the remainder of the ice core chronologies. The authors provide a nice description of the uncertainty methodology at the end of the supplement, but stop short of investigating the uncertainty during a specific period and explaining how and why the uncertainty varies. I think this would be most useful and probably worthy of being in the paper itself rather than at the end of the supplement."

=> This is an important point. We agree that more explanations are needed about how and why the uncertainty changes. We will add some more details in the revised version. As for include this in the paper itself, we think this is a bit tricky as the methodology is the same for both Bazin et al. and Veres et al.. We think this should stay in the SOM to be associated with both papers, but we leave the final decision to the editor.

An example on how the uncertainty calculation works for 4 different ice cores is presented in Figure 1. In the absence of any absolute or stratigraphic tie-points, the uncertainty will only be given by the variance associated with background scenario, hence much larger in the case of TALDICE than for EDC given our parameterization of variance (Table 2, SOM). Then, in the neighbouring of stratigraphic or absolute tie-points, the uncertainty will be decreased according to (1) uncertainty of the tie-point itself and (2) age uncertainty of the second ice core used in the case of stratigraphic tie-point. In Figure 1, we can separate different phases:

- From 0 to 11 ka, the main tie-points are stratigraphic tie-points using volcanic signature in the ice. The uncertainty associated with these tie-points is small, as well as the uncertainty associated with thinning function and accumulation rate (close to present-day conditions and small depth). The smallest uncertainty for Antarctic ice core is observed for EDML because its stratigraphic links are given with respect to NorthGRIP, whose chronology is given with a very small uncertainty.

- Between 11-17 ka, we still have few volcanic links but the chronology is mostly induced by methane links to the NorthGRIP ice core. Methane links are associated with larger uncertainties and with a more sparse resolution than volcanic tie-points. This leads to a general increase of the uncertainties of the Antarctic chronologies.

- The period 17-26 ka, roughly corresponding to MIS2, has the particularity of not being constrained with any marker for TALDICE. As a consequence the final error is only function of the background parameters variances, leading to an important increase of the chronology uncertainty especially for the TALDICE chronology that has the largest background variance for the thinning.

- Between 26 and 40 ka, we observe again the presence of (few) volcanic and (much more) methane links, reducing the chronology confidence to the same level as before (200-300 a).

- Around 40 ka, we observe a reduced uncertainty in all Antarctic ice core chronologies. This is due to the presence of the Laschamp event recorded as an absolute age marker

on EDC and reflected in the other ice cores through the volcanic and methane links.

"A different area I would like the authors to discuss more fully is how the physics of ice flow are included. Certain tie points were excluded because the thinning function became unreasonable. What was the criteria used? Also, there are many examples where deeper layers have thinned less than shallower layers. One prime example is the period 550 to 590 ka in the EDC record. The thinning function at 540 ka is 0.07, goes to .12 at 560 to 580 ka and then falls to 0.04 at 600 ka. It seems unlikely this can be ascribed to differences in rheology as the isotopic and chemical impurity concentrations of the ice between 600 and 620 is quite similar to between 560 and 580 ka. Despite the large change in thinning function, the uncertainty values are quite low (less than 2500 years). Doesn't a large change in thinning function indicate something strange is going on and the uncertainty should be quite large? I would like the authors to be more specific in their criteria for evaluating the thinning function and in particular discuss the ice flow conditions that would lead to deeper layers having thinned less than shallow layers. What influence is the background scenario having during this period?"

=> The physic of the ice flow used for background parameters is the simplest possible using 1D modelling. We agree that there are not real objective ways now to decide if the thinning function is unrealistic or not. This is an important limitation in our approach today on which we want to make progress by including data from ice fabrics and microstructure (see answer to comment of J. Severinghaus). This is already an on-going project that will answer this comment that we fully share. In the meantime, because of our current limited knowledge of the validity of background thinning function, we have associated a quite large variance to this parameter.

We concentrate now on the example proposed by reviewer 3 for the variation of the thinning function between 540 and 600 ka (Figure 2). This variation is quite strange and was also present in the final EDC3 chronology because the same δ18Oatm constraints were used (Parrenin et al., 2007b). Such a strange behaviour of the thinning function is also in agreement with strange ice fabrics observed at these depths. In our test for obtaining the final chronology, we have also tested to implement only δO2/N2 age markers. These age markers amplified slightly the discrepancy between the background thinning function and the output thinning function but basically confirm the new thinning function. In this case, we have thus good arguments for taking this output thinning function for EDC as robust. The age uncertainty associated with the thinning function at this depth scale is mainly given by the uncertainty of the age markers. We have compared age differences between three cases: with all δO2/N2 and δ18Oatm markers, when the two δO2/N2 age markers are removed (blue crosses on Figure 2), and without any δ18Oatm and δO2/N2 markers (Table 1). We then think that we should keep these two age markers; this will be corrected in the paper. Table 1 also shows the important increase of the age uncertainty when no constraints are present over this period (no tie-points). We are also currently working on obtaining more independent age markers through 10Be, lava dating and air content record of EDC to check this particular behaviour of the EDC thinning function.

Table 1 is presented in figure 3.

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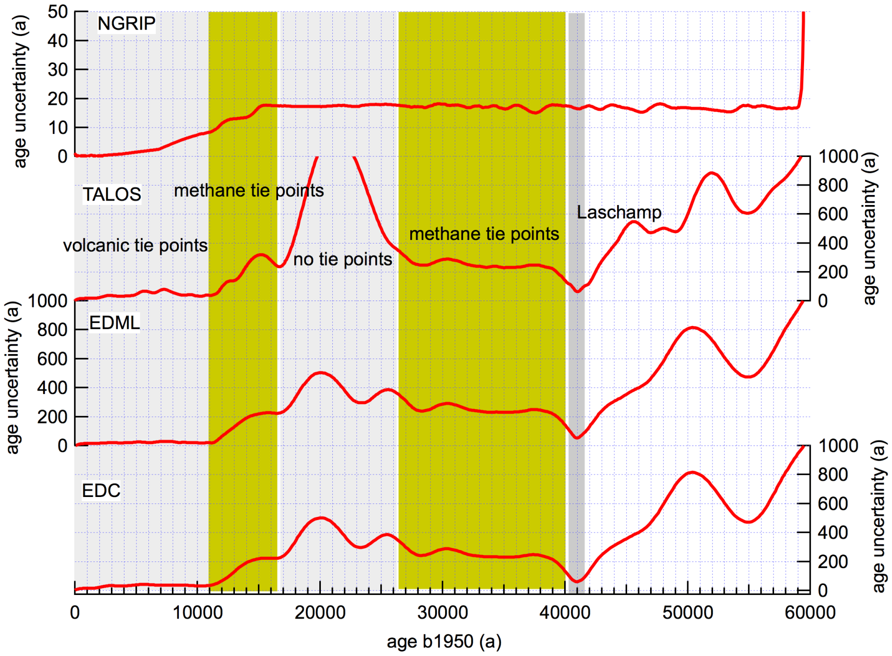

Fig. 1. AICC2012 uncertainty for EDC, EDML, TALDICE and NGRIP over the last 60 ka.

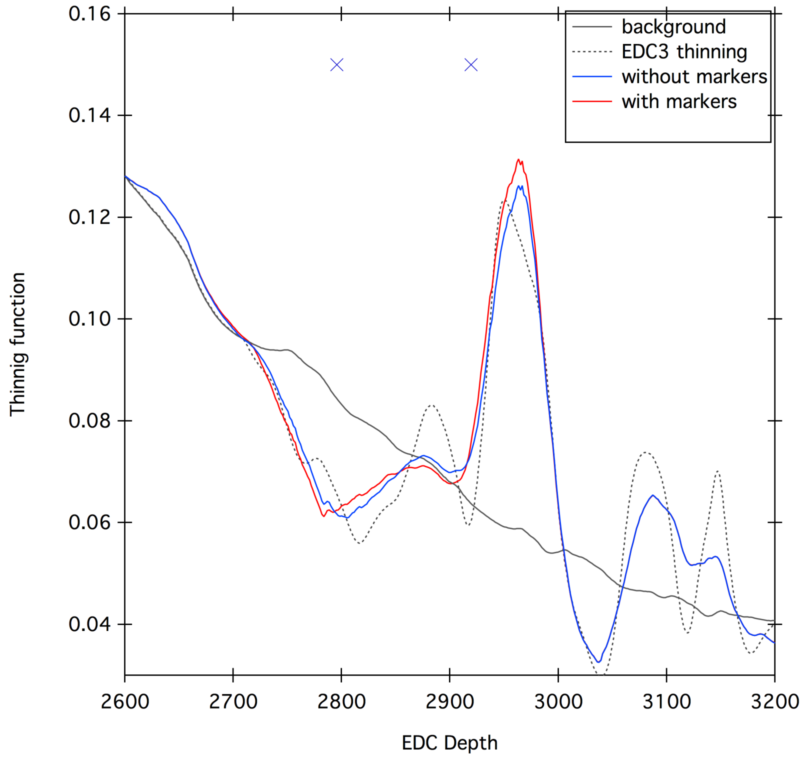

Fig. 2. Thinning function at EDC between 540-600 ka. Blue crosses mark the position of δO2/N2 age markers in the kept (red curve) and removed (blue curve) cases.

	Peak one (2783.55 m)	Peak two (2965.05 m)	Difference with no tie-points	
AICC2012 (without markers)	429816 (± 4005) a	569971 (± 2534) a	4597 a	6917 a
With markers	430760 (± 3688) a	570116 (± 2509) a	5541 a	7062 a
no tie-points	425219 (±6492) a	563054 (±38571) a		

Fig. 3. Table 1: Comparison of ice age at the maximum of the two main peaks of thinning.