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An improved North-South synchronization of ice core records around the 41 K beryllium 10 peak

Grant M. Raisbeck[1], Alexandre Cauquoin[2], Jean Jouzel[2], Amaelle Landais[2], Jean-Robert Petit[3], Vladimir Y. Lipenkov[4], Juerg Beer[5], Hans-Arno Synal[6], Hans Oerter[7], Sigfus J. Johnsen[8, #], Jorgen P. Steffensen[8], Anders Svensson[8], Françoise Yiou[1]

[1]CSNSM, CNRS, Université Paris-Saclay, Bats 104-108, 91405 Campus, Orsay, France
[2]LSCE/IPSL, CEA-CNRS-UVSQ), CEA Saclay Orme des Merisiers, 91191 Gif-sur-Yvette, France
[3]LGGE, CNRS, BP 96, 38402, St Martin d'Hères cedex, France
[4]Arctic and Antarctic Research Institute, 38 Bering St., St. Petersburg 199397, Russia
[5]Eawag, Überlandstrasse 133, Postfach 611, 8600 Dübendorf, Switzerland
[6]Laboratory of Ion Beam Physics, ETH Zurich, 8093 Zurich, Switzerland
[7]Alfred Wegener Institute for Polar and Marine Research, 27570 Bremerhaven, Germany
[8]Centre for Ice and Climate, Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[#]deceased

Correspondence to: Grant M. Raisbeck (Grant.Raisbeck@csnsm.in2p3.fr)

Abstract. Using new high resolution ^{10}Be measurements in the NGRIP, EDML and Vostok ice cores, together with previously published data from EDC, we present an improved synchronization between Greenland and Antarctic ice cores during the Laschamp geomagnetic excursion ~41 ky ago. We estimate the precision of this synchronization to be ± 20 years, an order of magnitude better than our previous work. We discuss the implications of this new synchronization for making improved estimates of the difference between ice and enclosed gas of the same age (delta depth), difference between age of ice and enclosed gas at the same depth (delta age) in the EDC and EDML ice cores, spectral properties of the 10Be profiles and phasing between Dansgaard/Oeschger-10 (in NGRIP) and AIM-10 (in EDML and EDC).

1 Introduction

In a previous study, we have synchronized the Greenland GRIP and Antarctic Dome C ice cores using the structured peak of cosmogenic ^{10}Be at ~41 ka resulting from a combination of the low geomagnetic intensity and variable solar activity during the Laschamp geomagnetic excursion (Raisbeck et al. 2007). The estimated precision of this synchronization was 200 years, due mainly to uncertainties associated with the GRIP ^{10}Be record (sample time resolution of 25-50 years, corrections for loss of ^{10}Be on 0.4 micron filters for some samples, several missing samples). We improve this situation significantly here by using a much higher resolution (5-10 year) ^{10}Be profile in the NGRIP ice core. In addition we report and synchronize high resolution ^{10}Be profiles from the peak region of two other Antarctic cores, EDML and Vostok. With these improvements, we estimate the uncertainty on the synchronization to be ± 20 years at our new tie points, and ± 35 years over the whole

Laschamp event. This precision is supported by the study of Svensson et al. (2013) who, on the basis of our earlier synchronization, have identified 3 volcanic signals which they believe are common to the Greenland and Antarctic cores.

2 Methods

A continuous series of 55 cm long bag samples from the NGRIP core were available from 2102 m to 2140 m. Each of these were cut into five 11 cm samples weighing ~100 g, and representing 5-10 years. The samples were treated and measured on the Gif sur Yvette Tandetron AMS facility as described in Raisbeck et al. (2007). AMS measurements were made relative to NIST $^{10}Be/^{9}Be$ standard SRM 4320, assuming a nominal value of $2.68x10^{-11}$. While the value of $2.79x10^{-11}$ has now been adopted by many groups for this standard, for consistency we continue to use the value that was used for all the previous measurements at the Gif sur Yvette Tandetron. Since this factor is constant, it has no effect on our synchronization procedures. An average of 400 ^{10}Be ions were counted for each sample, and the estimated precision (not including the uncertainty of the standard) was ~7%.

Vostok was one of the sites (the other being the original Dome C site) where the ^{10}Be peak discussed here was initially found (Raisbeck et al., 1987). Although the estimated date was younger than presently accepted, and the origin uncertain, it was already pointed out there that such a peak was a potentially interesting stratigraphic marker. Those initial measurements were made on discontinuous samples from the Vostok 3G core. We subsequently made measurements on a nearly continuous sequence of 1 m samples from the 4G core, which showed a double humped peak (Raisbeck et al. 1992). It was in an effort to look for even finer structure that the measurements shown here were made. These samples were ~10 cm in length and weighing >500g, were taken from the 5G core between 580-620 m. As can be seen in Fig. 1d, the sampling depth is not centered on the peak. This is because the sampling was based on the initial identification in 3G and, as we discovered, there is apparently a ~10 m offset between 3G and 5G. Since these measurements were carried out >15 years ago, also at the Gif AMS facility, the sample preparation and measurement procedures are those described in Raisbeck et al. 1987. For almost all samples at least 1000 ^{10}Be ions were counted, leading to an estimated measurement uncertainty of ~ 6%.

The EDML ^{10}Be measurements were performed at ETH Zurich with a sample preparation that is based on the common procedure already applied for the GRIP ice core (Yiou et al., 1997; Muscheler et al., 2004). Samples of 25 cm length corresponding to ~15 year resolution and a typical weight of 110 g were melted and processed without any further filtering. The $^{10}Be/^{9}Be$ ratios were measured using the compact AMS facility Tandy at ETH Zurich (Müller et al., 2010) resulting in uncertainties <3%. Results were normalized to the internal standard S2007N with a reference value of $^{10}Be/^{9}Be$ = $(28.1\pm0.8)*10^{-12}$ (Christl, et al., 2013).

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The climate records are provided by high resolution isotopic profiles (either δD or $\delta^{18}O$) measured along these ice cores. δD is used as primary climate indicator for Vostok and Dome C while $\delta^{18}O$ is used for NGRIP and EDML. In addition to existing water isotopic records, new high resolution measurements have been performed for this study on the Vostok 5G ice core (10 cm) and EDML (50 cm). These isotopic data are shown in Fig. 1a to 1d, with in addition a smooth curve (see legend).

From the ^{10}Be concentrations, ^{10}Be fluxes of the 4 cores were calculated using smooth versions of accumulation rate estimates from water isotopes, ice thinning and dating constraints by Parrenin et al (2007) for EDC, Ruth et al. (2007) for EDML, Parrenin et al. (2004) for Vostok, and NGRIP Project Members (2004) directly deduced from the ss09sea timescale (Johnsen et al., 2001) for NGRIP. Alternative accumulation rate determinations were obtained more recently through dating exercises such as for the AICC2012 timescale. These determinations do not show significant differences with previous determinations over our period of interest (Bazin et al., 2013; Veres et al., 2013; Andersen et al., 2006; Lemieux-Dudon et al., 2015). Only for the NGRIP ice core was it recently suggested that the mean accumulation rate of the MIS 3 could be overestimated by 20-30% (Guillevic et al., 2013; Kindler et al., 2014; Lemieux-Dudon et al., 2015). Still, even when using this modified accumulation rate, the shape of the variations of ^{10}Be flux on the Laschamp event recorded at NGRIP is not significantly affected. This is because for our purpose, it is the relative accumulation rates which are important.

3 Results

The results for the ^{10}Be concentrations and fluxes of the 4 cores are shown in Fig. 1 as a function of their depth along with their stable isotope profiles. As previously noted (Yiou et al. 1997, Raisbeck et al 2007) all cores show a highly structured peak of ^{10}Be centered on AIM-10 (EDC, EDML, Vostok) or DO-10 (NGRIP). It is this structure that allows us to make multiple synchronizations over the whole width of the peak, as shown in Fig. 2. This synchronization was done in two ways. Initially we selected 5 tie points (4 peaks and one valley, Table 1 and Fig. 2) along the profile which appeared to us to be clearly common to all the profiles, and synchronized using the AnalySeries program of Paillard et al (1996). Subsequently, in an effort to avoid the subjectivity of choosing tie points, we did the synchronization using the MATCH protocol of Lisiecki and Lisiecki (2002). The difference between these two procedures never differed by more than 42 years for NGRIP-EDC and 27 years for NGRIP-EDML. The maximum difference for the two procedures was for the period between tie points C and D, and was very small (<10 years) near the tie points. This confirms our visual impression that the chosen tie points are indeed the most robust common features of the profiles. For Vostok, we were unable to get a satisfactory synchronization for the MATCH protocol without imposing severe restrictions. This is probably due to several missing sample sections for that record.

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In order to estimate the precision of our synchronization, we can look at the volcanic correlations of Svensson et al. (2013). Starting from our earlier ^{10}Be synchronization, and layer counting results in both NGRIP and EDML, those authors identified 3 volcanic spikes they believed were common to NGRIP-EDML, 2 of which are linked to EDC by Severi et al. (2007). In Table 1 and Fig. 3, we show the position of those events as found by our improved ^{10}Be synchronization. For EDML the differences are 66 cm (~44 yr) for L1, 51 cm (~28 yr) for L2 and 44 cm (~24 yr) for L3. In EDC the differences compared to those given by Svensson et al. (2013) are 27 cm (~23 yr) for L2 and 36 cm (~31 yr) for L3. It can be noted that the age differences are systematic, having an average value of 27±7 years for L1 and L2. Thus the relative predicted ages between EDML and EDC for L2 and L3 differ by less than 10 years, consistent with their identification as the same event by Severi et al. (2007).

As mentioned above, we believe our tie points have the most robust synchronized ages. It is therefore reasonable to expect the difference in predicted ages to increase with distance from those tie points. However L1 is an exception, having the largest difference (44 years) despite being the nearest (~1 m) to a tie point (BeC). If that tie point is correct, it is thus reasonable to question whether L1 is indeed a bipolar event. In fact L1 was not listed as one of those used by Severi et al. (2007) to correlate EDC with EDML, although that might be because of lower resolution in EDC.

If L2 and L3 are indeed bipolar events, and L1 is not, we estimate from the above that the uncertainty in our synchronization is ≤35 years over the whole Laschamp event, and ≤20 years at our tie points, an order of magnitude better than our previous work (Raisbeck et al. 2007). This shows that, at least in regions where there is significant structure in ^{10}Be profiles, it is possible to link Greenland and Antarctic climate records with decadal precision. As pointed out by Svensson et al. (2013), using such correlation as a framework, it may be possible to find other common volcanic signals in ice cores from the two hemispheres.

4 Spectral properties of the ^{10}Be profiles

As indicated in the Introduction, the centennial variations in the ^{10}Be profiles are believed to be caused by variations in solar activity. For example, during the Holocene, Steinhilber et al (2012) found periodicities of 88 years (*Gleissberg* cycle) and 210 years (*de Vries* cycle) in a composite of tree ring ^{14}C and ice core ^{10}Be records. For the Laschamp period, Wagner et al. (2001) reported a ~205 year periodicity of ^{10}Be in the GRIP core. It is thus interesting to do a spectral analysis on the higher resolution and better quality NGRIP 10Be record reported here. This is shown in Fig. 4, where a very significant (> 99%) 200 year signal is found in the Fourier spectrum (REDFIT program of Schulz and Mudelsee (2002)). As can be seen in the wavelet spectra however (MATLAB package of Grinsted et al. (2004)), this periodicity is really only significant for a short interval near the end of the time period studied. While there is also a short interval where an 88 year periodicity appears, this is not significant in the Fourier spectrum.

Since we now have the EDC and EDML ^{10}Be profiles synchronized on the NGRIP time scale, we might expect these to show similar periodicities. Somewhat to our surprise, however, this is only partially the case. While both show a ~200 year signal in the same time region of the wavelet analyses, these are barely significant (~90%) in the Fourier spectra. This is because that peak appears to be distorted by longer signals of ~290 years and 350 years in EDC and EDML respectively. This is consistent with the observation of Cauquoin et al. (2014) who found that the 210 year periodicity in the EDML Holocene data used by Steinhilber et al. (2012), the only Antarctic core in their composite, was only significant over short and sporadic time periods. It is also consistent with the fact that Cauquoin et al. (2014) did not find any evidence for this periodicity in ^{10}Be from EDC during the interval 336-325 ka BP. It thus appears that there may be meteorological effects in the Antarctic which tend to diminish or interfere with the ^{10}Be production signal recorded in the ice, compared to Greenland.

5 Implications for Delta Depth and Delta Age Estimates

Using preliminary values of our previous ^{10}Be synchronization, together with methane correlations, Loulergue et al. (2007) estimated the difference in depth (delta depth) and age (delta age), between the ice and gas records in EDC and EDML. The discrepancy they found at EDC compared with the classical firn densification model (Goujon et al. 2003) was in fact the first hard evidence that this model was inadequate for glacial ice from low accumulation sites in Antarctica. This had important implications for the EDC4 gas age construction. Loulergue et al. (2007) hence proposed that the delta age obtained by the Goujon et al. (2003) model using temperature and accumulation rate deduced from water isotopes (scenario 1 in Fig. 6 and Loulergue et al., 2007) was not appropriate. Instead, delta age for the EDC gas age was calculated with the Goujon et al. (2007) model but with a modified accumulation rate (scenario 4 in Fig. 6 and Loulergue et al., 2007). The accumulation rate of scenario 4 was adapted so that the calculated delta age at 41 ka was in agreement with the delta age determination using ^{10}Be and CH_4 synchronization.

In the construction of the AICC2012 chronology (Bazin et al., 2013; Veres et al., 2013), a different approach for the delta age calculation has been chosen. The construction of AICC2012 relies on the use of a bayesian tool, DATICE [Lemieux-Dudon et al., 2010], to optimize the chronology of 5 ice cores using absolute dating constraints and stratigraphic links in the gas and ice phases. The AICC2012 delta age calculation for EDC is hence constrained by the CH_4 and ^{10}Be data as in Loulergue et al. (2007). It also benefits from the recent finding of Parrenin et al. (2012) showing that the firn lock-in depth at Dome C during the last deglaciation was best determined from δ^{15}N measurements in air trapped in ice cores rather than by outputs of firn modeling. As a consequence, the background scenario used for the lock-in depth and hence the delta age in the construction of the AICC2012 chronology for EDC was based on δ^{15}N measurements performed at Dome C (Dreyfus et al., 2010; Landais et al., 2013) leading to a significantly smaller delta age than the firn model output for EDC during the glacial period.

Using the 5 tie points from the present synchronization, we have used a slightly modified version of the technique described by Loulergue et al. (2007) to calculate delta depth of EDC and EDML. Instead of correlating the methane profiles at a single point, we have correlated the whole profiles using the Match protocol (Fig. 5). Then, a delta age has been determined for each ^{10}Be peak. The resulting delta ages and delta depths (Fig. 6), are in reasonably good agreement with the delta age and delta depths calculated using scenario 4 in Loulergue et al. (2007). Our results are also in good agreement with the AICC2012 delta age at EDC hence validating the chosen approach for delta age calculation.

6 Implications for Bipolar Seesaw and Stable Isotope Interpretation

The last glacial period is characterized by a succession of millennial-scale climatic events identified both in Greenland and in Antarctica. In Greenland, the climate shifts are very abrupt with a temperature shift between a cold Greenland stadial (GS) to a warm Greenland interstadial (GIS) designated as Dansgaard-Oeschger events (DO). In Antarctica the temperature changes of the corresponding climatic events are much smoother, and are designated as Antarctic Isotopic Maxima (AIM). A clear relationship has been demonstrated between DO and AIM events: each DO events is associated with an AIM (EPICA community members, 2006; Jouzel et al., 2007) and the temperature/isotopic maximum of the AIM occurs approximately synchronously with the Greenland abrupt temperature increase. The observed relationship between Greenland and Antarctica temperature evolutions led to the proposed theory of the bipolar seesaw (Broecker et al., 1998; Stocker et al., 1998). The global picture of the bipolar seesaw can be explained by a simple modeling of a slow thermal response of Antarctic temperature to Greenland abrupt warmings and coolings through a heat reservoir in the southern ocean (Stocker and Johnsen, 2003).

The knowledge of the exact relative timing between DO events in Greenland and AIM events in Antarctica is limited by the ice core chronologies. Usually, Greenland and Antarctic ice cores are synchronized using the global atmospheric signals in the air trapped in ice core (CH_4, $\delta^{18}O$ of O_2). However, the climatic signals are recorded in the ice phase through water isotopic composition. Because the entrapped air is systematically younger than the entrapping ice, by centuries to millennia, accurately determining this age difference is crucial for the Greenland vs. Antarctica phasing.

Recent studies have permitted to significantly decrease the age uncertainty on Greenland vs. Antarctica climatic sequences. This has been done through an increase in the number of stratigraphic links between Greenland and Antarctic ice cores (e.g. Schüpbach et al., 2012; Svensson et al., 2013) and new high resolution Antarctic records at relatively high accumulation sites, hence with small ice – air age differences (WAIS-Divide Project Members 2015). These recent improvements have

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revealed a refined sequence of Greenland vs. Antarctic climatic changes during the last glacial period. First, a comparison of several climatic records in Antarctica with the Greenland sequence has highlighted regional differences in the shape of the AIM events and in the phasing between the temperature increase in Antarctica and the abrupt temperature change in Greenland over the long GS's that are associated with a strong discharge in Northern Atlantic, i.e. Heinrich Stadials (Buiron et al., 2012; Landais et al., 2015). Second, an accurate dating exercise on the west Antarctica WDC ice core over the last 60 ka suggests that the decrease of Antarctic temperature occurs ~200 years after the abrupt temperature increase in Greenland (WAIS-Divide Project Members 2015). This has been interpreted as a "northern push for bipolar seesaw" (van Ommen, 2015). Still these studies suffer from the same limitation associated with the ice – air age difference and rely on determination on the past depth of the firn, based on firn densification and/or measurements of $\delta^{15}N$ of N_2 in the trapped air.

Here we use the direct synchronization of NGRIP with EDC, EDML and Vostok based on the ^{10}Be records. In Fig. 7 we show the climate ^{10}Be synchronized records of the 4 cores, as represented by the δD and $\delta^{18}O$ profiles. Comparing the 3 Antarctic records, one can observe that, while they have the same general features, there are also significant differences in detail. These are probably due to meteorological effects such as seasonal variation of isotopic ratios, depositional effects, etc. This shows that one must be careful to not over interpret details of individual stable isotope profiles in low accumulation regions of the Antarctic as a climate proxy. This is particularly evident in the Vostok 5G profile, which differs significantly from the previously published profile from the 3G core (Jouzel et al. 1987).

We confirm the general Greenland vs. Antarctica relationship observed by Raisbeck et al. (2007) with the increase in δD or $\delta^{18}O$ in Antarctica leading the abrupt $\delta^{18}O$ increase in NGRIP by several centuries, which is a classical feature of the bipolar seesaw, operating here for a small DO (AIM) event. The high resolution of our water isotopes and ^{10}Be records also enables us to look at the fine scale Greenland vs. Antarctica temporal relationship around the abrupt warming recorded at NorthGRIP. For this, we have used the same statistical approaches as in WAIS-Divide Project Members (2015), respectively the BREAKFIT software by Mudelsee [2010] and a similar automated routine (referred to as MATLAB routine in Table 2) using a second-order polynomial (rather than a linear for BREAKFIT) fit to the data. The water isotope profiles for the 3 Antarctic sites show several wiggles associated with a variability of ~100 – 200 years. Despite this variability, it is still possible to identify a maximum for AIM 10 using the aforementioned statistical tools. Thus defined, the maximum is not synchronous in each Antarctic record. The maximum is reached at EDML, ~210 years before the abrupt Greenland warming, while the maximum detected at Dome C appears to be ~140 years later. As for Vostok, because of poor resolution in the water isotopic records, the maximum is not clearly identified and no clear lead/lag between abrupt Greenland temperature increase and maximum water isotopic value associated with AIM 10 can be determined. To complete this study, we have also determined similarly the shift between the abrupt Greenland warming and the maximum in the water isotopic record at WAIS, and found that the WAIS maximum is ~142 years earlier.

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This result seems at first sight to contradict the conclusions presented in WAIS-Divide Project Members (2015) using the same approach for the determination of the breakpoint. In both the EDML and WDC ice cores, we find that the maximum in Antarctica for AIM 10 is reached more than 140 years before the Greenland warming. This suggests one must be cautious in drawing a conclusion about a general mechanism for AIM vs. D/O dynamics based on a stack of several D/O – AIM events, as proposed in WAIS-Divide Project Members (2015). Indeed, the lead / lag of Greenland vs. Antarctica may be different from one event to another. This is evident from Fig. 8 where the maximum of AIM 7, 8 and 10 clearly leads the abrupt warming in Greenland both at WDC and EDML. Such a behavior is not unexpected. Indeed, it has already been suggested that the sequence of the abrupt variability of the last glacial period (length and frequency of GS and GIS) can be affected by the long term (orbital) climatic variability (Schulz et al., 2002; Capron et al., 2010). Moreover, for GS associated with an occurrence of Heinrich events, it has been evidenced that a decoupling exists between the Greenland or high latitude climate and lower latitudes with Greenland remaining in a cold stable phase while lower or southern hemisphere latitudes exhibit significant climatic variations (Barker et al., 2015; Guillevic et al., 2014; Rhodes et al., 2015; Landais et al., 2015). In addition, as previously noted, a significant regional variability affects the sequence of the AIM in Antarctica. For AIM 10, we indeed observe different timing for the maximum in EDC, WDC and EDML. Such a different behavior for the sequence of AIM in Antarctica has already been observed between different drilling sites (Buiron et al., 2012; Landais et al., 2015). The difference observed for AIM 10 between EDML and EDC confirms such previous findings.

Our finding on the phasing between DO and AIM 10 for the different Antarctic sectors and the comparison with other DO – AIM sequence calls for cautiousness in interpreting AIM isotopic stacks for timescale of the order of centuries. At this timescale, stacking may not be relevant because of regional variability in Antarctica and diversity in the amplitude, shape and frequency of the AIM along the last glacial period.

7 Conclusion

We have shown here that in periods where there are significant production variations of ^{10}Be, it is possible to synchronize Greenland and Antarctic ice cores with decadal precision. This in turn means that the climate and other environmental parameters registered in these ice cores can be synchronized at this same precision, thus allowing different models and mechanisms to be more finely tested.

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Event	depth NGRIP (m)	GICC05 age (years b2k)	depth EDML observed (m)	depth EDML predicted*** (m)	depth EDC observed* (m)	depth EDC predicted*** (m)	depth Vostok 5G (m)
BeA	2106.01	40563	1362.28		731.65		598.16
BeB	2109.62	40794	1366.56		734.55		600.75
L1	2111.58	40912	1369.54	1368.88		735.94	
BeC	2113.22	41002	1370.57		736.97		603.99
L2	2115.41	41109	1372.73	1372.22	738.19**	737.92	
L3	2118.62	41249	1375.15	1374.71	739.80**	739.44	
BeD	2129.82	41858	1386.61		746.68		614.86
BeE	2132.64	42067	1390.49		749.17		617.40

*EDC 97 depth
**from Svensson et al using EDML-EDC correlation of Severi et al. (2007)
***from ^{10}Be synchronization

Table 1: In the first two colummns, are reported the depth and ages (GICC05) of the ^{10}Be tie points and the volcanic markers of Svensson et al., (2013) at the NGRIP site (see text). The following columns provide the depths of corresponding depths for EDML, EDC and Vostok ice cores either observed or predicted.

Age difference of the inflexion point with respect to the mid-slope of abrupt warming in NGRIP	MATLAB algorithm (WAIS-Divide Project Members, 2015)	BREAKFIT software (Mudelsee, 2010)
EDML (this study)	-213 ± 40 years	-207 ± 50 years
EDC (this study)	+130 ± 30 years	+150 ± 50 years
Vostok (this study)	Non significant	Non significant
WDC, WAIS-Divide Project Members (2015)	-156 ± 50 years	-129 ± 50 years

Table 2: Phasing between NGRIP GS – GIS transition and AIM for different Antarctic ice cores over DO-AIM 10.

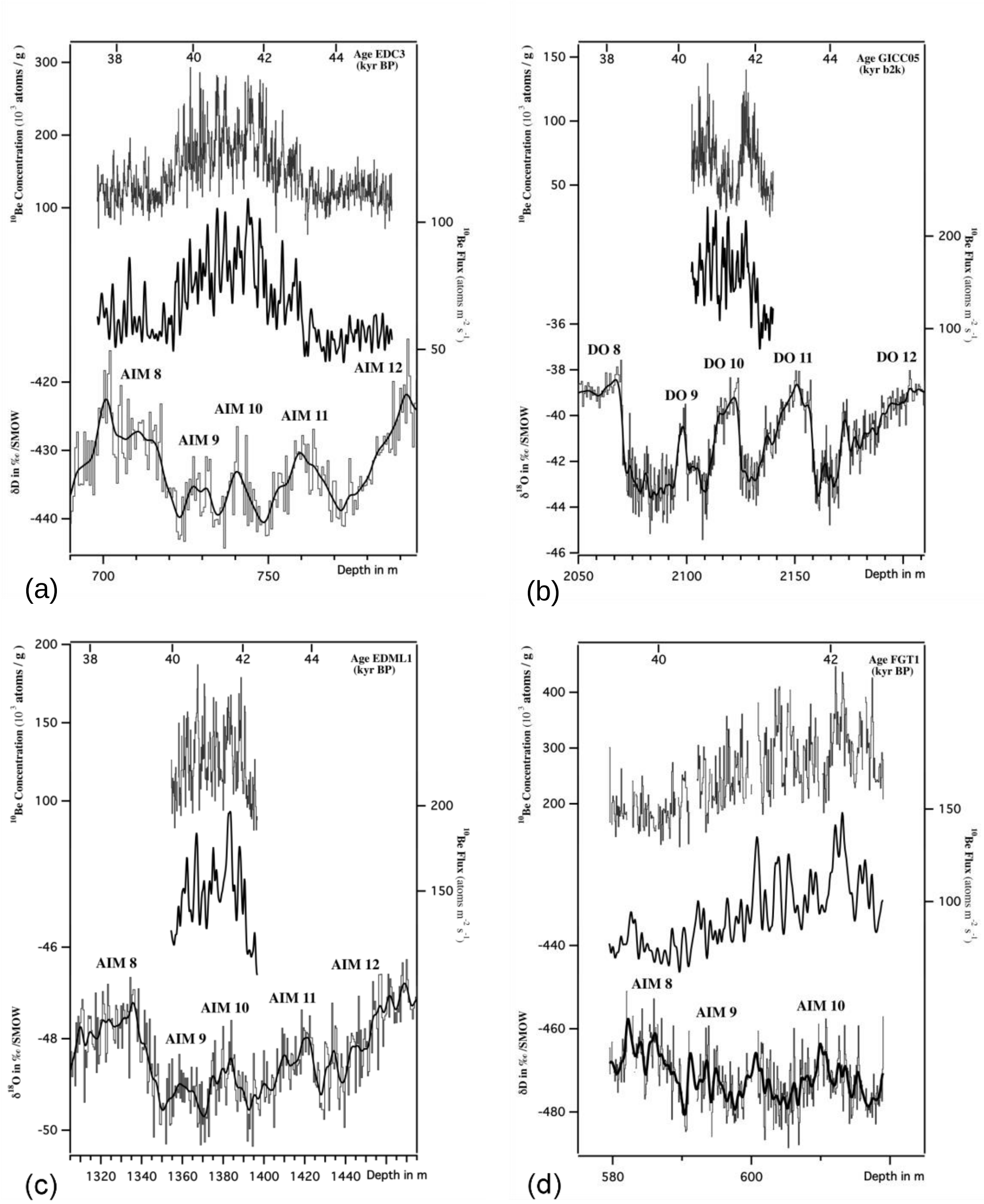

Figure 1: ^{10}Be concentrations, ^{10}Be flux and stable isotope profiles (δD or δ^{18}O) and their running averages as a function of depth and age in 4 ice cores a) EPICA Dome C; EDC3 timescale (Parrenin et al., 2007), b) NGRIP; GICC05 timescale (Andersen et al., 2006), c) EDML; EDML1 timescale (Ruth et al., 2007), and d) Vostok: FGT1 timescale (Parrenin et al., 2004). As in Raisbeck et al. (2007), the ^{10}Be flux has been calculated using accumulation rates used in the above timescales and smoothed with a 50 year binomial filter. AIM stands for Antarctic Isotope Maximum.

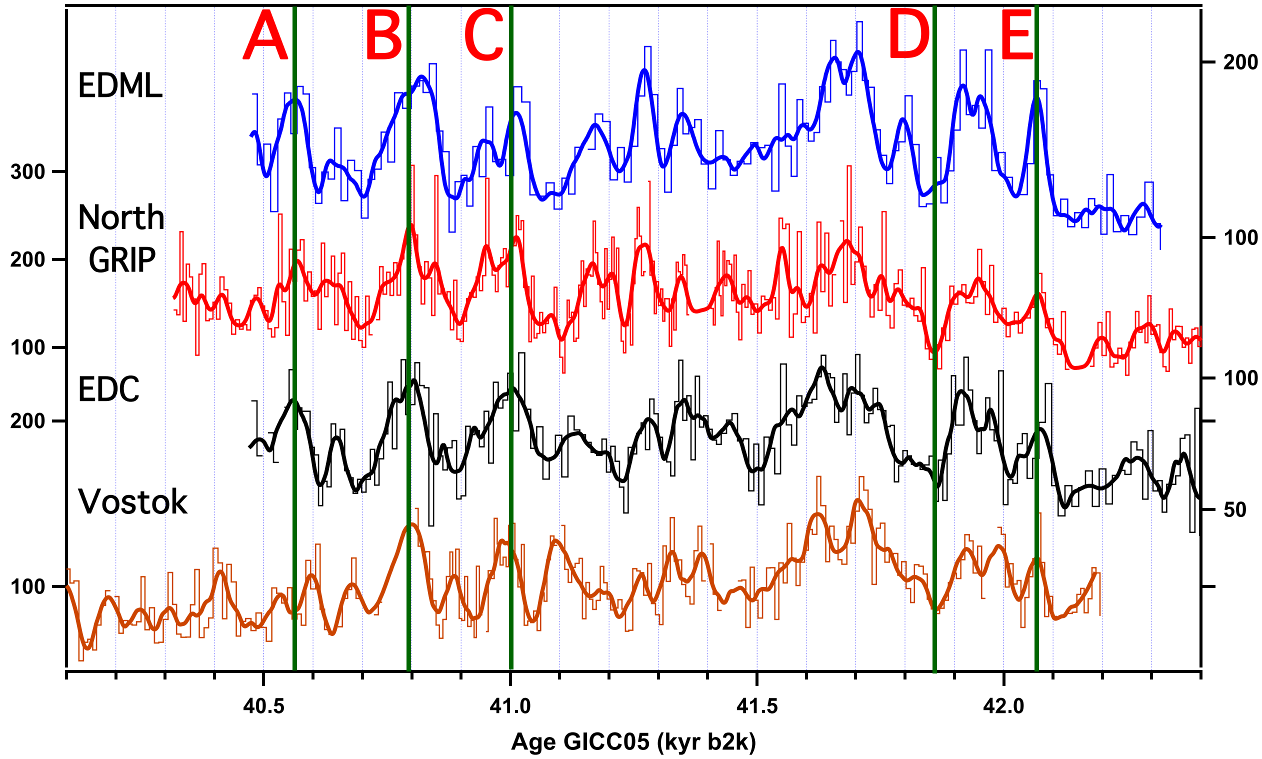

Figure 2: Beryllium 10 fluxes after synchronisation to NGRIP (GICC05) using Match protocol (Lisiecki and Lisiecki, 2002) for EDC and EDML, or using 5 tie-points (A-E) and Analyseries (Paillard et al., 1996) for Vostok. For each site the detailed fluxes and a curve smoothed with a 50 year binomial filter are shown.

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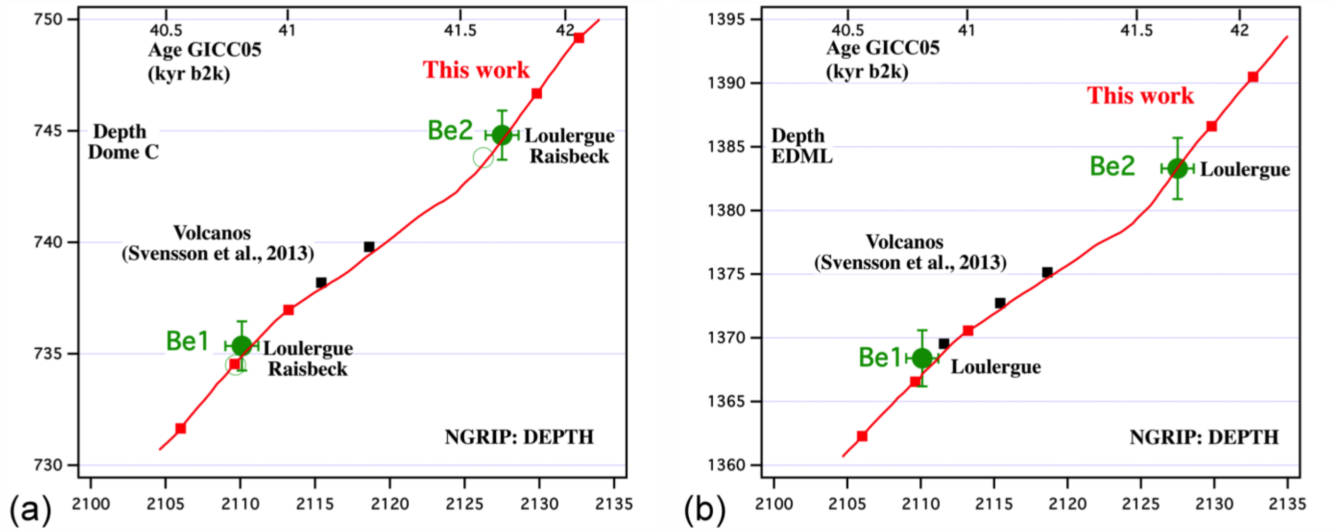

Figure 3: Comparison of the different tie points between NGRIP and Dome C (a) and between NGRIP and EDML (b) as derived from beryllium-10 from this work (red squares), from Loulergue et al. (2007) (green full circles) and from Raisbeck et al. (2007) (green empty circles) with in addition (full black squares) the tie points deduced from volcanoes (Svensson et al., 2013). We have indicated the uncertainty for the tie points used in Loulergue et al. (2007). For the new ^{10}Be and volcanic tie points, the uncertainties are smaller than their symbols.

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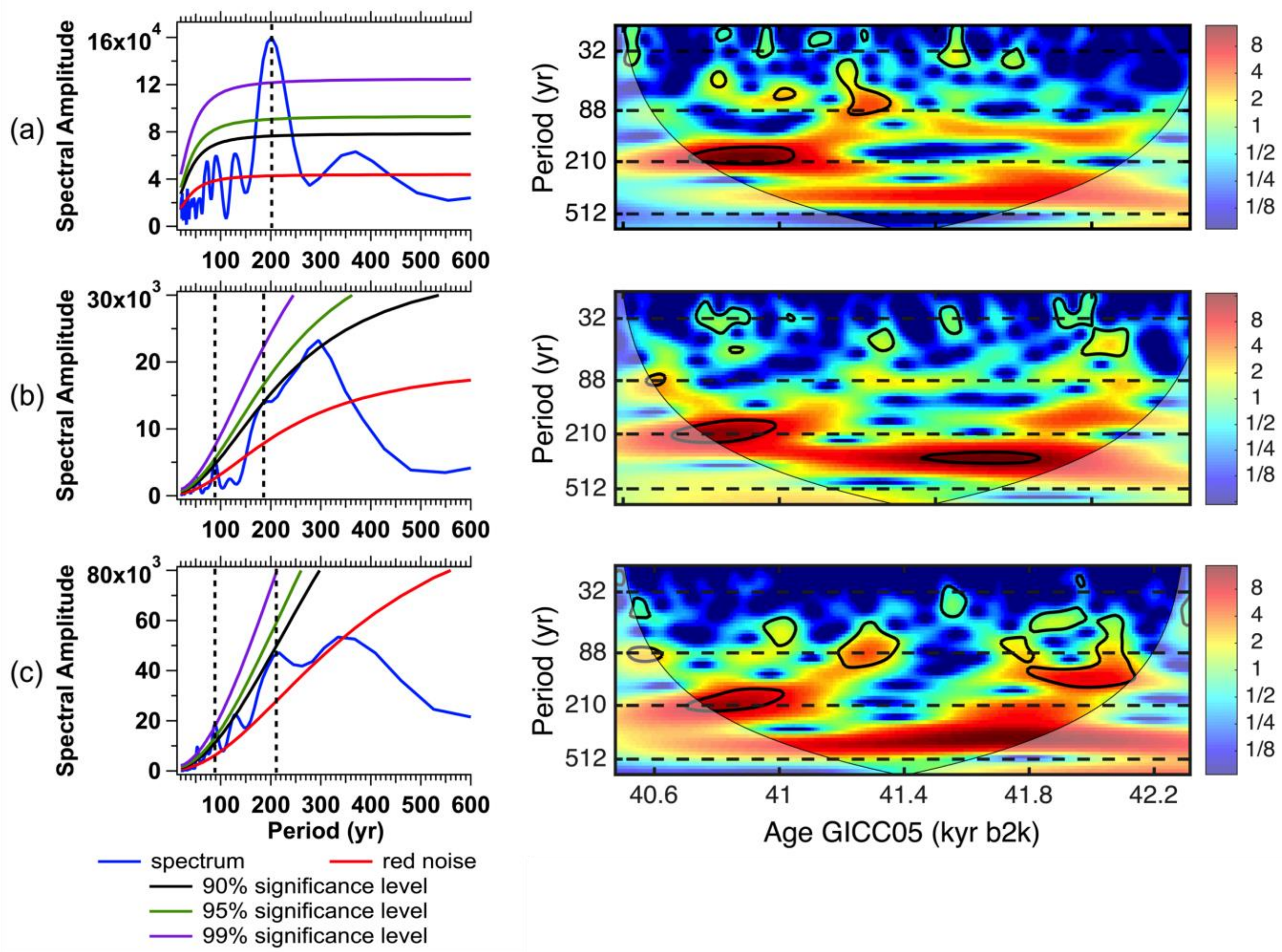

Figure 4: Fourier (left) and wavelet (right) analyses of our ^{10}Be flux records at (a) NGRIP, (b) EDC and (c) EDML from 40.480 to 42.320 kyr b2k on the GICC05 age scale. The solid black lines on the wavelet panels indicate the regions which are significant at 95% level.

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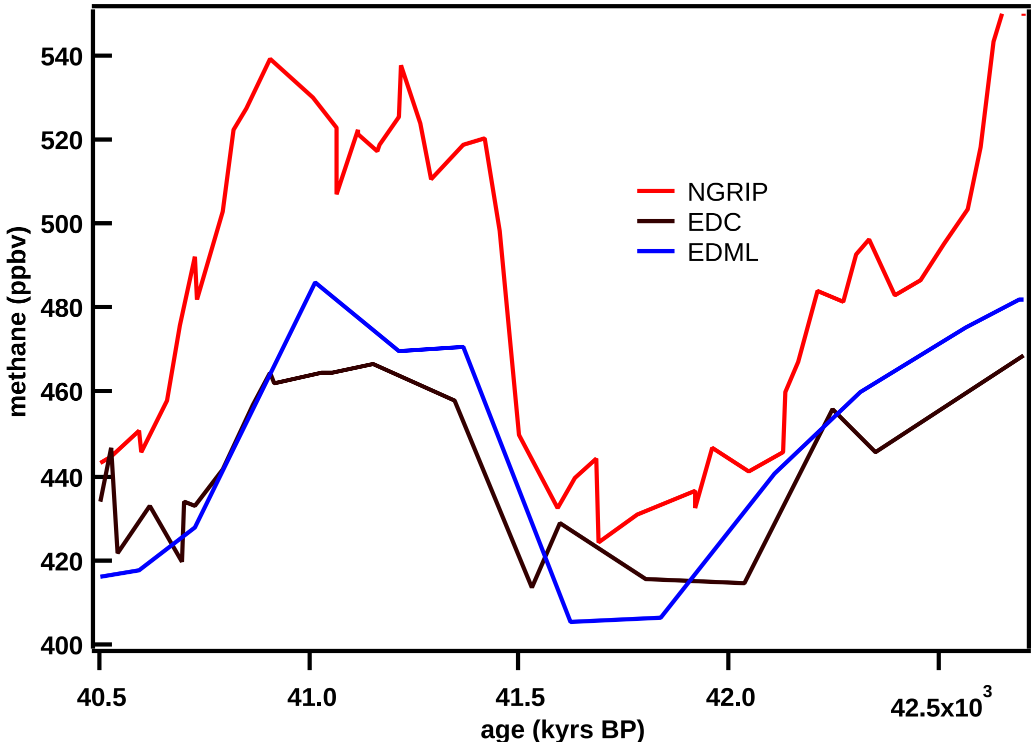

Figure 5: Synchronization of the methane profile from NGRIP with EDC and EDML profiles. The methane data are from Baumgartner et al. (2014) for NGRIP, Loulergue et al. (2008) for EDC and Schilt et al. (2010) for EDML.

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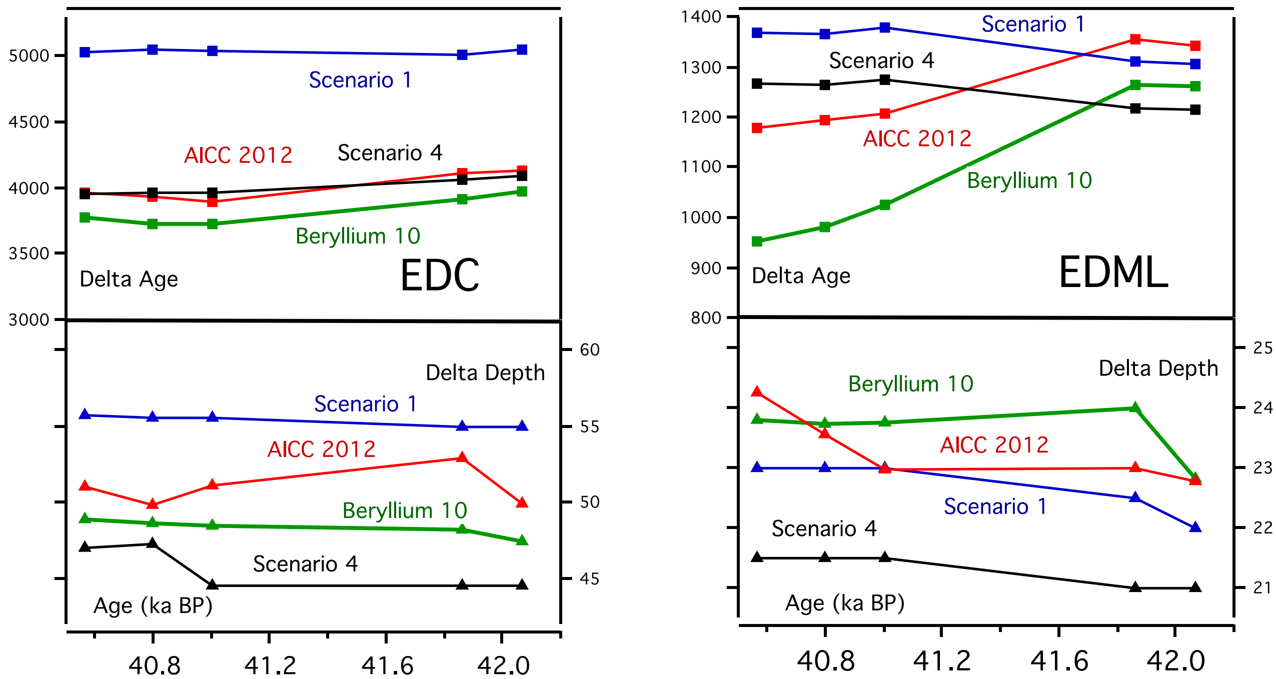

Figure 6: Delta age and delta depth derived for the 5 beryllium 10 tie points derived in this work compared with their values as used in scenario 1 and 4 (Loulergue et al., 2007) and for AICC2012 (Bazin et al., 2012).

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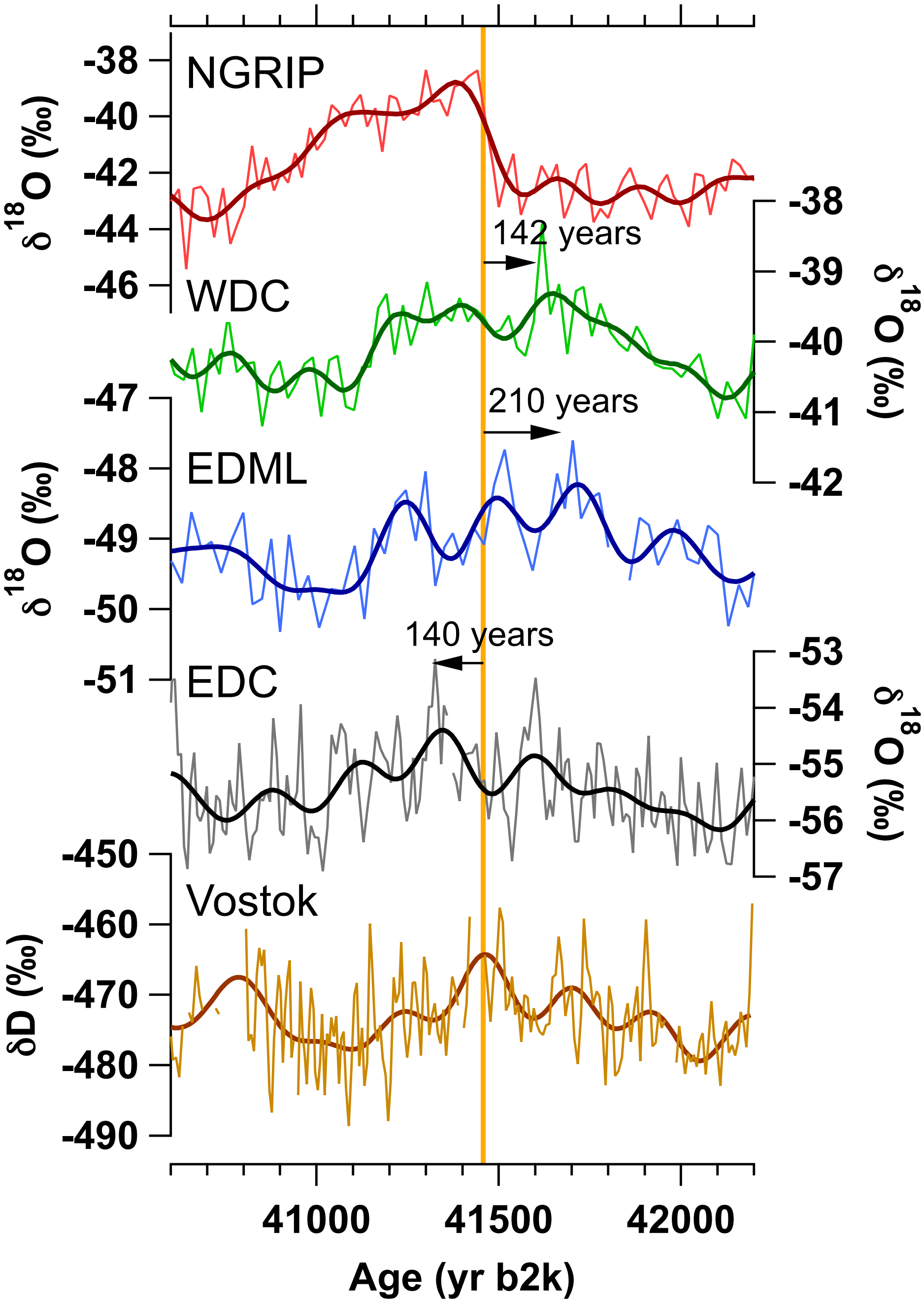

Figure 7: Phasing between the GS-GIS transition in Greenland (vertical orange line) and the maximum of the AIM in 4 different Antarctic ice cores on the GICC05. The synchronicity between Vostok, EDC, EDML and NGRIP is based on the 10Be records while the WDC isotopic record has been drawn on the GICC05 timescale using the correspondence between the WSD timescale and GICC05 given in Buizert et al. (2015). In addition to the high resolution water isotopic profiles, a low pass filter at 200 years has been drawn for NGRIP, EDML and EDC.

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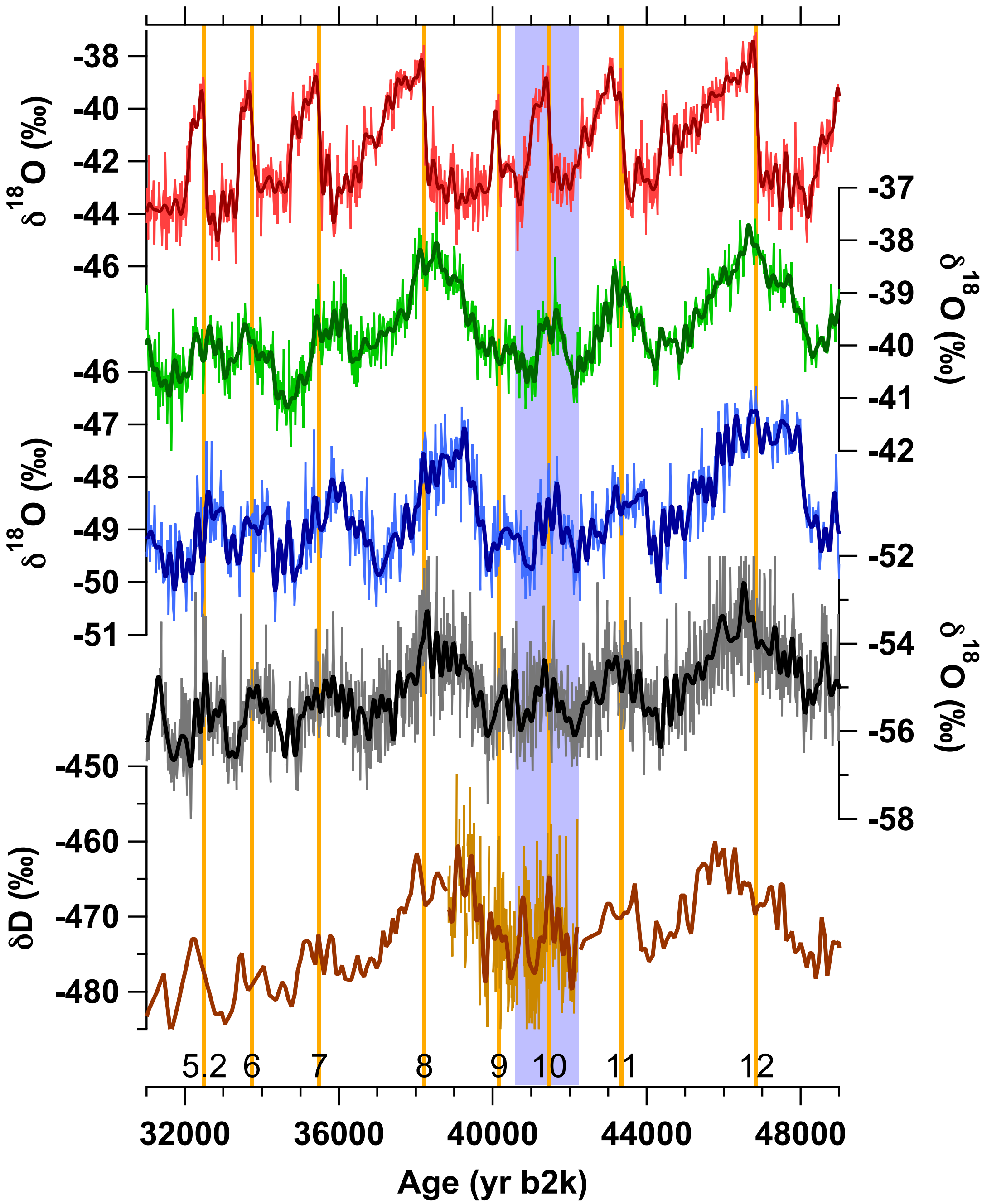

Figure 8: Water isotopic records for NGRIP and 4 Antarctic ice cores over DO events 5 to 12 on the GICC05 timescale with the transition between GS and GIS indicated by the vertical orange lines. The order and color of the curves are the same as Fig. 7. The synchronization between NGRIP, Vostok, EDML and EDC is based on the AICC2012 timescale while the WDC record has been transferred on the GICC05 timescale as WD2014 in Buizert et al. (2015).