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# New constraints on the gas age-ice age difference along the EPICA ice cores, 0–50 kyr

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## Abstract

Gas is trapped in polar ice sheets at ~50–120 m below the surface and is therefore younger than the surrounding ice. Firn densification models are used to evaluate this ice age-gas age difference (Δage) in the past. However, such models are not well tested on low accumulation and cold sites of the East Antarctic plateau, especially for periods with different climatic conditions. Here we bring new constraints to test a firn densification model applied to the EPICA Dome C (EDC) site for the last 50 kyr, by linking the EDC ice core to the EPICA Dronning Maud Land (EDML) ice core, both in the ice phase (using volcanic horizons) and in the gas phase (using rapid methane variations). We use the structured $^{10}$Be peak, occurring 41 kyr before present (BP) and due to the low geomagnetic field associated with the Laschamp event, to experimentally estimate the Δage and Δdepth during this event. It allows us to evaluate the model and to link together climatic archives from EDC and EDML to NorthGRIP (Greenland). Our results reveal an overestimate of the Δage by the firn densification model during the last glacial period at EDC. Tests with different accumulation rates and temperature scenarios do not entirely resolve this discrepancy. Our finding suggests that the phase relationship between $CO_2$ and EDC temperature inferred at the start of the last deglaciation (lag of $CO_2$ by 800±600 yr) is overestimated and that the $CO_2$ increase could well have been in phase or slightly leading the temperature increase at EDC.

## 1 Introduction

The timing of climatic events in the two hemispheres is a key information for a better understanding of the mechanisms of climate change. Comparison of Greenland and Antarctic ice records can be accomplished using atmospheric gas records as correlative tools. Ice cores from high accumulation rate sites are preferable as they minimize uncertainties in the difference between the age of the gas and the age of the surrounding ice matrix (Δage) (Schwander et al., 1997). Atmospheric trace gases with lifetimes exceeding the interhemispheric mixing time and showing significant changes in the past, can be considered as time markers on a global scale. The most prominent trace gases measured routinely on extracted air from ice cores are carbon dioxide, methane and nitrous oxide ($CO_2$, $CH_4$, $N_2O$) (Stauffer et al., 2002; Siegenthaler et al., 2005; Spahni et al., 2005). Additionally available is the isotopic composition $\delta^{18}O$ of $O_2$ ($\delta^{18}O_{atm}$), a proxy for biologic productivity and ice volume changes (Sowers et al., 1993). Atmospheric $CH_4$ and $\delta^{18}O_{atm}$ records are preferentially used for synchronisations during the last glacial period. The reconstructed $CO_2$ concentration suffers from in situ production in Greenland ice cores (Anklin et al., 1995), and $N_2O$ shows sporadic artefacts occurring in depth intervals with elevated dust concentrations, hence in ice covering glacial time periods (Sowers, 2001; Stauffer et al., 2003). $CH_4$ is of special interest for three reasons: the past atmospheric signal is reliably recorded in ice cores from both polar regions, it shows large temporal concentration variations, and it closely follows Greenland rapid climatic variability during the last glaciation and deglaciation (Chappellaz et al., 1993).

Several studies have already used the $O_2$ isotopes and/or the $CH_4$ concentration to constrain the climatic relation between the hemispheres at the last glacial inception (Landais et al., 2004), the last glaciation (Bender et al., 1994; Blunier et al., 1998; Blunier and Brook, 2001) and the last deglaciation (Blunier et al., 1997; Steig et al., 2002). Best information about the timing of climate events comes from high-resolution gas records which have absolute or synchronized timescales with uncertainties smaller than 500 yr (Blunier and Brook, 2001). Based on the methane correlation it has been proposed that for each large Dansgaard-Oeschger (DO) event in Greenland exists a corresponding warming event in Antarctica (Blunier et al., 1998; Blunier and Brook, 2001). The abrupt DO warming in Greenland is preceded by a slower warming in Antarctica. In addition Antarctic temperatures peak at about the time of the abrupt warming in Greenland. This north-south interaction suggests a strong teleconnection between the two poles through heat transport by the ocean circulation (Stocker and Johnsen, 2003). This connection feature has been termed “bipolar seesaw”. Recently a high-resolution methane record combined with a detailed isotopic profile was produced from the EDML ice core in Antarctica (EPICA Community Members, 2006). It indicates that even the smaller DO events in Greenland have a counterpart in Antarctica. The amplitude of the Greenland warming appears to be linearly correlated with the duration of the preceding warm phase in Antarctica. EDML is indeed an interessant ice core, located in the Atlantic sector of Antarctica, showing this one-to-one coupling.

The gas dating tool provides a relative chronology between ice cores, not an absolute dating. The quality of this relative chronology strongly depends on how accurate the calculation of the Δage is. The latter can be estimated by a firn densification model assuming that we know the ice chronology and the past variations of surface temperature and accumulation rate at the site of deposition. Δage is small and very well determined in Greenland over the last glacial period, due to the relatively high accumulation rate. This characteristic of Greenland ice cores further allows annual layer counting as used in the new ice chronology GICC05 for NorthGRIP (Andersen et al., 2006; Rasmussen et al., 2006; Svensson et al., 2006; Vinther et al., 2006). In addition to the model results, Δage can be determined directly from the Greenland ice core itself. The abrupt Greenland surface warmings induce a temperature gradient in the firn column. This temperature gradient causes isotopically heavier molecules to migrate towards the cold end. This thermal diffusion affects the isotopic ratios of atmospheric nitrogen and argon, which are thought to be constant over time in the atmosphere.

Therefore, anomalies of the isotopic ratios allow to calculate the amplitude of fast temperature changes in the past. Further, they set the start point of these changes in the gas record. Since the temperature variation is recorded in the isotopic composition of the ice and in the isotopic composition of the gases of the enclosed air, the difference of the respective depths (Δdepth) is directly accessible. With an underlying timescale we find also the corresponding Δage, e.g. for each DO event individually. Unfortunately, in Antarctica, thermal diffusion produces isotope anomalies usually too small to be detected. In addition, the lower accumulation rate results in relatively uncertain Δage calculations.

One way to improve the accuracy of Δage estimates in Antarctica is to rely on a stratigraphic marker recorded in the ice matrix of two ice cores. This allows the correlation of the ice records in addition to the gas correlation. The $^{10}$Be anomaly (Raisbeck et al., 2002) provides such a marker. It is observed as a highly structured peak believed to be due to a low geomagnetic field associated with the Laschamp Event (Mazaud et al., 1994), centered at 40.4±2 kyr BP (Guillou et al., 2004). Yiou et al. (1997) and Raisbeck et al. (2002) showed that this $^{10}$Be peak is contemporary with the DO event # 10.

Here we present new $CH_4$ data obtained on the EDC ice core ($75^{\circ\prime}$ S, 123° E, 3233 m a.s.l., 25 $\text{kg m}^{-2}\,\text{yr}^{-1}$) over the last 55 kyr BP (before AD 1950), that complement recently published $CH_4$ data along the EDML ice core (75° S, 0° E, 2892 m a.s.l., 64 $\text{kg m}^{-2}\,\text{yr}^{-1}$) (EPICA Community Members, 2006) and a stack of Greenland $CH_4$ records (Blunier et al., 2007). We then evaluate different accumulation and temperature scenarios against the objective that the Δage at EDC and EDML obtained by the densification model should produce 1) two consistent gas age scales at EDC and EDML; and 2) a North-South synchronisation compatible with the one obtained from the $^{10}$Be peak during the Laschamp event.

## 2 Data

### 2.1 Ice chronologies

When evaluating the ice/gas difference (as a function of age at the same depth – hereafter Δage – or as a function of depth at the same age – hereafter Δdepth) with a firn densification model, a chronology for the ice has to be imposed.

For the NorthGRIP core, we use the GICC05 chronology obtained by annual layer counting from 0 to 42 kyr BP (Andersen et al., 2006; Rasmussen et al., 2006; Svensson et al., 2006; Vinther et al., 2006. The uncertainty of GICC05 is around 1.6 kyr at the location of the $^{10}$Be peak. Its GICC05 age of 41.2 kyr BP matches recent independent estimates within a few centuries (Svensson et al., 2006). Note that the uncertainty on the time spent between two nearby depth levels (which can be expressed as e.g. the number of uncertain counted layers per meter) is smaller than the error on the absolute ages, the latter being cumulative with depth.

The new EDC ice chronology (hereafter EDC3, Parrenin et al., 2007[1]) is based on a relatively simple ice flow model applied to ice domes. Several control age windows are used (from absolutely dated horizons and from comparison to others paleoclimatic records) to constrain the free parameters of the model via an inverse method (Parrenin et al., 2001). For the last 50 kyr, EDC3 is matched onto GICC05 (Parrenin et al., 2007[1]) at several tie points: during the last 6 kyr (by $^{10}$Be-$^{10}$Be synchronization), during the last deglaciation (by methane-isotope synchronization) and during the Laschamp event (by $^{10}$Be-$^{10}$Be synchronization).

The corresponding chronology for EDML (hereafter EDML1, Ruth et al., 2007) has been derived by synchronizing the EDML and EDC ice cores using volcanic and dust tie points based on continuous sulfate, electrolytic conductivity, dielectric profiling, particulate dust and $Ca^{2+}$ data available for both cores (Severi et al., 2007). Due to common changes in the Patagonian dust source strength and the hemispheric significance of major volcanic eruptions, this procedure is justified. For the last 75 kyr (the period of interest in this study), the synchronization is mainly based on unambiguous volcanic markers recorded in the sulphate parameter, providing a synchronization to better than ±100 years (on average ±35 years, Ruth et al., 2007).

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[1] Parrenin, F., Barnola, J.-M., Beer, J., Blunier, T., Castellano, E., Chappellaz, J., Dreyfus, G., Fischer, H., Fujita, S., Jouzel, J., Kawamura, K., Lemieux, B., Loulergue, L., Masson-Delmotte, V., Narcisi, B., Petit, J.-R., Raisbeck, G. M., Raynaud, D., Ruth, U., Schwander, J., Severi, M., Spahni, R., Steffensen, J. P., Svensson, A., Udisti, R., Waelbroeck, C., and Wolff, E.: The EDC3 agescale for the EPICA Dome C ice core, Clim. Past Discuss., submitted, 2007.

## 2.2 Temperature and accumulation parameterizations

Δage estimates from a firn densification model (Pimienta et al., 1987; Arnaud et al., 2000; Goujon et al., 2003) require knowing the history of surface temperature and accumulation rate at the site of deposition. Below we present the temperature and accumulation parameterizations that will be used further on.

Accumulation rate $A$ and temperature $T$ are deduced from the deuterium content of the ice $\delta$D, through the following relationships:

$$T = T^0 + \alpha \Delta \delta D_{\mathrm{corr}} \tag{1}$$

$$A = A^0 \exp \beta \Delta \delta D_{\mathrm{smo}} \tag{2}$$

where $A^0$ and $T^0$ are surface accumulation and temperature for the present. $\Delta\delta D_{\mathrm{corr}}$ corresponds to the present-day value $\delta D_0$ isotope corrected for the variations in temperature and isotope at the source of the air masses (Parrenin et al., 2007). The latter is determined through isotopic reconstructions of benthic foraminifera (Bintanja et al., 2005). $\Delta\delta D_{\mathrm{smo}}$ is a 50-yr running average of $\Delta\delta D_{\mathrm{corr}}$ (to remove the noise of water isotopic ratios unrelated with accumulation rate changes). $\alpha$ represents the spatial slope of the present-day isotopic thermometer. $\beta$ is a corrective factor influencing the glacial-interglacial relationship between accumulation rate and $\delta$D changes.

As EDML was measured for $\delta^{18}$O instead of $\delta$D, the following relationship is used

$$\delta D = 8 \cdot \delta^{18} O + 10 \tag{3}$$

The present-day isotopic content, temperature and accumulation rates are respectively $\delta D_0$=–396.5‰, $T^0$=217.5 K, $A^0$=2.84 cm-of-ice/yr for EDC (Parrenin et al., 2007 (5)) and $\delta D_0$=-351.22‰, $T^0$=228.65 K, $A^0$=6.4 cm-of-ice/yr for EDML (supplementary material, EPICA, Community Members, 2006).

Equation (2) leads to an average glacial accumulation rate at the EDML drill site of about 2.9 cm WE/year (EPICA Community Members, 2006), a value not far from

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the present one of Dome C (2.5 cm WE/year) (EPICA Community Members, 2004). Furthermore, smooth modifications of the accumulation rate at EDC were applied in order to match EDC3 onto GICC05 back to 41 kyr BP (Parrenin et al., 2007[1]), creating some artefacts of the accumulation rate during early Holocene.

## 2.3 Methane records

We use $CH_4$ records from EDC and EDML back to 55 kyr BP (Fig. 1) (EPICA Community Members, 2006). For EDC, the resolution of the existing methane data (Spahni et al., 2005) has been doubled (leading to an average temporal resolution of 93 years) and extra samples were analyzed around DO 8 to 11 corresponding to the location of the $^{10}$Be peak. The measurements were performed at Bern and Grenoble with a wet extraction technique. Details of the method can be found in Chappellaz et al. (1997). For consistency with previously published EDC and EDML $CH_4$ data sets, the $CH_4$ mixing ratios obtained at LGGE are increased by 6 ppbv to be in accordance with the Bern values (Spahni et al., 2005). The measurement uncertainty is ±10 ppbv (Chappellaz et al., 1997).

## 2.4 The 41 kyr $^{10}$Be peak in Greenland and Antarctic ice cores

$^{10}$Be has been measured in detail on the EDC (Raisbeck et al., 2002, 2007[2]) and GRIP (Yiou et al., 1997) ice cores, depicting the full structure of the peak at 41 kyr BP. The uncertainty of the position of two sub-peaks during the Laschamp event is about ±1.1 m for both cores. The $^{10}$Be record at NorthGRIP is not completed yet. Therefore the position of the $^{10}$Be sub-peaks at NorthGRIP is based on GRIP-NorthGRIP isotopic synchronization (Svensson et al., 2006). The uncertainty associated with this GRIP-NorthGRIP synchronization is neglected here (NorthGRIP Community Members, 2004).

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[2] Raisbeck, G. M., Yiou, F., Jouzel, J., and Stocker, T. F.: Direct North- South Synchronization of abrupt climate change records in ice cores using be10, in preparation, 2007.

For EDML, the $^{10}$Be peak has not yet been measured. To determine its probable location in the core, we use the synchronization through volcanic horizons between the EDML and EDC cores (Severi et al., 2007). The estimated depths of the two $^{10}$Be subpeaks in the EDML core are shown in Table 1. The uncertainty of the corresponding depths is ±0.23 m and ±0.35 m (Ruth et al., 2007).

## 3 Empirical constraints on EDC and EDML Δages

Two types of empirical constraints on the EDC and EDML Δages are used. The first is based on EDC and EDML ice (sulphate) and gas (methane) synchronisation during the last glacial period (Sect. 3.1). The second involves their synchronisation to NorthGRIP during the Laschamp event (Sect. 3.2).

### 3.1 EDC-EDML $CH_4$ synchronisation

As the ice of the two EPICA ice cores is well synchronized via volcanic horizons (±35 years, Severi et al., 2007; Ruth et al., 2007 ), a correct estimate of Δage/Δdepth at both sites should lead to synchronised $CH_4$ records in the gas phase. We use the sharp methane transitions to define match points between the two cores, taken at middle slope of each $CH_4$ sharp increase and decrease (Table 2), and to evaluate the correctness of the two modelled Δage/Δdepth.

Note that contrary to the information inferred by comparison to NorthGRIP during the Laschamp event, this constraint is only relative. Hence, we do not infer an estimate of Δage (or Δdepth) at each site, but we determine if two scenarios of Δage (or Δdepth) at each site are consistent. The accumulation rate being more than twice as large at EDML than at EDC, its Δage is smaller and better constrained. Consequently, the EDML-EDC methane synchronisation brings more constraints on the EDC Δage.

In the following, this empirical constraint will be referred to as the EDC-EDML constraint.

## 3.2 Δage and Δdepth constraints during the Laschamp event

Δage and Δdepth at the depth of the $^{10}$Be peak in the two EPICA cores is estimated by linking both their ice and gas signals to NorthGRIP. The ice link is obtained by $^{10}$Be-$^{10}$Be synchronisation for both $^{10}$Be sub-peaks. The gas link is obtained by matching the EPICA $CH_4$ records to the NorthGRIP isotopic record, assuming that these two records are synchronous during the rapid DO transitions (Huber et al., 2006).

### 3.2.1 The Δage method

The method is illustrated in Figs. 2 and 3 for EDC. One of the $^{10}$Be sub-peaks is found at the ice depths DC-$d_1$ at EDC and NG$-d_1$ at NorthGRIP. The corresponding GICC05 age is $a_1$. The age of the methane at the same EDC depth DC-$d_1$ is younger than the age $a_1$ with a difference of Δage. At EDC, the depth corresponding to the $^{10}$Be peak occurs during DO #8 in the gas phase. At EDML, the corresponding trapped gas occurs during DO #9 due to the smaller Δage. We synchronise this methane event with its concomitant NorthGRIP isotope event, being found shallower than the $^{10}$Be sub-peak at a depth NG-$d_2$ and with a GICC05 age $a_2$. Therefore, the age difference $a_1-a_2$ is an indirect measurement of the Δage at the EDC depth DC-$d_1$.

The overall uncertainty of this Δage corresponds to the square root of the sum of the uncertainties on:

1. the $^{10}$Be NorthGRIP-EDC synchronisation;
2. the isotope-methane NorthGRIP-EDC synchronisation;
3. the GICC05 age difference $a_1-a_2$, that is to say the number of uncertain annual layers between the NG-$d_1$ and NG-$d_2$ depths (which is much smaller than the uncertainty on the absolute age at these depths). Consequently, our Δage estimate is directly dependent on the GICC05 age scale.

EDC Δage with this method is found to be 3408±240 yr and 3692±315 yr for both EDC $^{10}$Be sub-peaks (Table 1).

The same procedure is applied for EDML, adding the uncertainty due to the EDML-EDC synchronisation through volcanic horizons. EDML Δage is found to be 909±286 yr and 892±364 yr (Table 1).

In the following, these empirical constraints will be referred to as the EDC-Δage and EDML-Δage constraints respectively.

### 3.2.2 The Δdepth method

The method is illustrated in Figs. 2 and 3. We start again by considering the EDC ice depth DC-$d_1$ of the $^{10}$Be sub-peak, and the corresponding NorthGRIP ice depth NG-$d_1$. Assuming that $CH_4$ and the Greenland isotopes change synchronously, the methane variation corresponding to the NorthGRIP isotope variation at depth NG-$d_1$ is found in the EDC ice deeper than the $^{10}$Be peak, at the depth DC-$d_2$. The gas age at DC-$d_2$ is identical to the ice age at DC$-d_1$, and the depth difference DC-$d_2$- DC-$d_1$ is an indirect measurement of Δdepth. With this method, uncertainties in the age scales are not relevant.

The uncertainty on the Δdepth evaluation corresponds to the square root of the sum of the uncertainties on:

1. the $^{10}$Be NorthGRIP-EDC synchronisation;

2. the isotope-methane NorthGRIP-EDC synchronisation.

Δdepth for the two $^{10}$Be sub-peaks amounts to 53.5±4.2 m and 53.1±4.2 m (Table 1).

The same procedure is applied to EDML, adding the uncertainty on the EDML-EDC synchronisation. Δdepth then amounts to 24.7±1.7 m and 25.1 m±1.7 m (Table 1).

In the following, these empirical constraints will be referred to as the EDC-Δdepth and EDML-Δdepth constraints respectively.

## 4 Testing firn densification model scenarios

We use the Arnaud firn densification model (Arnaud et al., 2000) which considers two densification processes: pure sliding of snow grains for density lower than ~0.55, and pure deformation of grains for density higher than ~0.55. Diffusion and advection of temperature in the firn are also considered, and lead to an average temperature at the close-off depth slightly higher than at the surface (Goujon et al., 2003).

In this section, we test different temperature and accumulation rate scenarios at EDC and EDML (supplemental material http://www.clim-past-discuss.net/3/435/2007/cpd-3-435-2007-supplement.zip) against the Δage and Δdepth empirical constraints described in section 2: EDC-EDML methane synchronisation, and Δage and Δdepth at the location of the $^{10}$Be peak.

### 4.1 Scenario 1: EDC3 and EDML1 temperature and accumulation histories

With the EDC3 chronology (Parrenin et al., 2007), the surface temperature history is deduced from the isotopic content of the ice without correction for source temperature variations. The $\beta$ coefficient in Eq. (2) has then been determined so that the resulting chronology agrees with the absolute age of the $^{10}$Be peak at 41 kyr BP. The inferred value is 0.0157. The accumulation rate has been further slightly modified in order to synchronize the EDC3 age scale onto GICC05 at several tie points (Parrenin et al., 2007[1]). For EDML, source temperature variations were not considered either and $\beta$ has been set to 0.015 (EPICA community members, 2006).

The $\alpha$ coefficient in Eq. (1) representing the spatial slope of the present-day isotopic thermometer is estimated empirically at EDC as 1/6.04‰/°K from the present day-surface measurements between Dumont d'Urville and Dome C (Lorius and Merlivat, 1977). For EDML, the value is estimated empirically as 0.82‰/°C from the relationship between $\delta^{18}$O and surface temperature in Dronning Maud Land (EPICA community members, 2006).

Overall, the EDC3 and EDML1 climatic inputs to the densification model provide a

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poor agreement with the empirical constraints (Table 3 and Fig. 4). The EDML gas time scale is always older than the EDC gas time scale (see Fig. 4), with an average difference of 850 yr. The difference ranges from 300 yr (Younger Dryas/ Holocene transition) to 1150 yr (onset of DO #6). This implies that either the EDC Δage is overestimated or the EDML one is underestimated. The discrepancy being smaller during the last deglaciation than during the last glacial period, the modelling error appears to get worse during cold conditions (Fig. 4).

At the time of the two $^{10}$Be sub-peaks, the EDC (EDML) modelled Δage amounts to 5050 yr and 5010 yr (1370 and 1320 yr), i.e. ~40% (50%) larger than the empirically derived values and well outside their confidence interval. The comparison is more favorable for the Δdepth constraints. The EDC (EDML) modelled estimates amounts to 55.3 m and 55.0 m (22.9 and 22.9 m) and are only slightly larger (smaller) than the empirical values, and within or at the limit of their confidence interval.

### 4.2 Scenario 2: EDC3 and EDML1 accumulation rate histories, reduced amplitude of glacial-interglacial temperature change

In scenario 1, the modelled Δage at both EDML and EDC is too large during the $^{10}$Be peak. One way to resolve this discrepancy is to reduce the amplitude of the glacial-interglacial temperature change. Relatively warmer temperatures lead to a faster densification process, a shallower close-off depth and a reduced Δage. In scenario 2 we keep the EDC3 and EDML1 accumulation rates unchanged (Sect. 3.1) and we reduce the glacial-interglacial temperature amplitude with a factor $1/\alpha=7.13‰/\mathrm{K}$. Note that this provides a better accordance between the measured and modelled borehole temperature.

This scenario generally gives a slightly better agreement than scenario 1 with the empirical constraints derived in Sect. 2 (Table 3 and Fig. 4). The difference between the EDC and EDML gas age scales is slightly reduced, with an average of 660 yr. During the $^{10}$Be sub-peaks Δage at EDC (EDML) is 4820 yr and 4800 yr (1330 and 1280 yr), around 35% (45%) higher than the empirical values. Δdepth at EDC (53.2 and 52.6 m) is now in excellent agreement with the empirical estimates. The agreement however slightly decreases for EDML Δdepth (22.2 and 22.8 m).

### 4.3 Scenario 3: EDC3 and EDML1 accumulation rate histories, EDC temperature corrected for source effects

The EDC3 temperature history is corrected for variations in the mean ocean isotopic composition, but not for source temperature variations. Vimeux et al. (2002) showed at Vostok that taking into account the latter reduces the amplitude of glacial-interglacial surface temperature change by up to 2°C. In scenario 3, we apply such correction using the deuterium excess record (Stenni et al., 2003 and new data, B. Stenni personal communication). In general, temperatures are warmer during the glacial period compared to scenario 1. The EDC accumulation rate history is kept identical to scenario 1, as well as the EDML temperature and accumulation rate histories.

Overall, this scenario gives results very close to scenario 2 (Table 3 and Fig. 4). The agreement between the EDC and EDML gas age scales is slightly improved, with an average shift of 630 yr. During the $^{10}$Be sub-peaks, the EDC Δage is 4820 yr and 4810 yr, around 35% higher than the empirical values. The EDC Δdepth (54.1 m and 53.5 m) is in excellent agreement with the empirical estimates.

### 4.4 Scenario 4: EDC3 and EDML1 temperature histories, reduced amplitude of glacial-interglacial accumulation rate changes

Another way to reduce Δage is to increase the past accumulation rate. In scenario 4, we choose $\beta$ to be 0.0094 for EDC and 0.0120 for EDML, the temperature histories remaining identical to scenario 1.

Overall this scenario provides an excellent agreement between modelled and empirical Δages, with an average shift of only –30 yr (Table 3, Fig. 4, 5a). There are two notable exceptions : during the last deglaciation, the EDML gas chronology is older than the EDC one by a few centuries, and vice versa during DO #9.

During the $^{10}$Be sub-peaks, EDC (EDML) Δage is 3970 yr and 4020 yr (1270 and 1220 yr), around 10–15% (35%) higher than the empirical values but almost within their confidence intervals.

Δdepth at EDC (44.5 m and 44.3 m) and EDML (21.7 m and 21.7 m) are now significantly smaller than the empirical estimates. Indeed, Δdepth is equal to the product of the close-off depth in ice equivalent (CODIE) by the thinning function. In this scenario, we increased the glacial accumulation rate while keeping the same ice chronology, and thus implicitly decreased this thinning function, thus leading to smaller Δdepths.

In Fig. 5b, the EPICA gas chronologies are compared to the NorthGRIP one. The Antarctic ice age scales being fitted to NorthGRIP only during the $^{10}$Be peak. Apart from this time period, a disagreement between the GICC05 age scale and the EDC or EDML gas age scale could result either from a wrong Antarctica-Greenland ice synchronisation, or/and from an error in the Δage estimates at the Antarctic sites. As expected, EDC and NorthGRIP chronologies agree well at the time of DO #8 (EDC gas trapped at the depth of the $^{10}$Be peak) and in a lesser margin between EDML and NorthGRIP at the time of DO #9.

## 5 Discussion

The comparison between our empirical constraints on EDC and EDML Δage and Δdepth and different firn densification modelling scenarios indicate that the official EDC3 and EDML1 ice chronology, temperature and accumulation rate histories are clearly inconsistent with the EDML-EDC methane synchronization constraint. Either the EDC glacial Δage is greatly overestimated or the EDML glacial Δage is greatly underestimated. The shift between the two gas chronologies roughly resembles the isotopic signal (being inversely correlated, Fig. 4), in contrast with Vostok and Byrd (Bender et al., 2006), where it covers a large range between +1500 yr and –2000 yr. The origin of the inconsistency between model outputs and the observation thus probably lies either in the parameterization of the climatic input to the model based on water isotopes or in the physical link in the model between climate conditions and the densification process, under colder and drier conditions than today.

A test of different temperature scenarios (scenarios 2 and 3) only removes a fraction of the disagreement with empirical constraints. These scenarios reduce the glacial-interglacial amplitude of temperature change by about 15%, which seems to be a maximum bound according to different evidences presently available for the East Antarctic plateau (Jouzel et al., 2003; Blunier et al., 2004). Salamatin et al. (1998) and Tsyganova and Salamatin (2004) suggest on the other hand a large underestimate of the temperature change, which would make even worse the disagreement between modelled and observed Δage and Δdepth. To our knowledge, there is no other study proposing a smaller amplitude of glacial-interglacial temperature change than the one deduced from the standard isotope/temperature relationship in Antarctica. In summary, only a small fraction of the disagreement can thus originate from the temperature scenario.

Using larger glacial accumulation rates at both EDC and EMDL (scenario 4) than those classically deduced from water isotopes, we are able to get a much better agreement between firn densification model outputs and Δage empirical constraints. But at EDC, it represents an average accumulation rate of 63% of the present-day value during the last glacial maximum, corresponding to an increase of more than 30% with respect to the EDC3 official scenario. However, changing the accumulation rate scenario implies a modification of the ice chronology. The EDC3 chronology is the product of the initial annual layer thickness (the initial accumulation rate) and the thinning function (evaluated with a mechanical ice-flow model, Parrenin et al., 2007[1]). Larger glacial accumulation rates (scenario 4) associated with the EDC3 thinning function leads to a younger chronology during the last glacial part. This is inconsistent with the fact that the EDC3 chronology is constrained within ~1 kyr at the location of the $^{10}$Be peak and that it is synchronized onto the NorthGRIP annual layer-counted GICC05 age scale (Andersen et al., 2006; Svensson et al., 2006).

Increased glacial accumulation rates as in scenario 4 are thus physically compatible with the ice core chronology only if they are compensated by a proportional decrease in the thinning function. However, the latter varies between 1 at the surface and 0.75 at 850 m of depth (∼50 kyr BP) and it is considered very well constrained under ice-flow conditions for the upper quarter of an ice dome (Parrenin et al., 2007[1]). A correction of about 30% of the thinning function in this EDC depth range thus seems unrealistic.

It could be argued that the EDML-EDC methane disagreement results from an underestimated Δage at EDML. However, EDML Δage during the last glacial amounts to 1000–1500 yr, and an underestimate of 800 yr (50 to 80%) is unrealistic. We can thus conclude that the firn densification model overestimates Δage at EDC during the last glacial period.

Because of the larger Δage at EDC, we can not assess the accuracy of the EDML firn modelling for the EDC-EDML $CH_4$ synchronisation. Only the $^{10}$Be peak shows that during this particular time period, EDML Δage is overestimated by ∼400 yr. This is still within the uncertainties estimated in the EPICA Community Members (2006) paper.

Such an inconsistency of EDC modelled gas ages has already been suggested by comparing them to the Byrd ice core constraints (Schwander et al., 2001), although the uncertainty on the EDC Δage was evaluated at ±10% by Schwander et al. (2001). Consequently, we suggest that an important phenomenon is missing in the firn densification model applied to the very cold and low accumulation conditions of the glacial Antarctic plateau, for which no present-day analogue exists so far. This leads to an overestimate of the close off depth, as already suggested by the $\delta^{15}$N data at Vostok (Sowers, 1992). The model has been tested over a large range of accumulation rate and temperature conditions and has proved to be realistic (Arnaud et al., 2000; Goujon et al., 2003). But conditions with –65°C mean annual temperature and ∼1 cm $H_2O$/yr accumulation rate apparently generate different snow surface structures and/or densification processes (and thus density profiles) compared with present-day conditions on the East Antarctic plateau, which are not yet represented in the physics of the model.

Apparently by chance, no such systematic bias between model and empirical Δage constraints was detected, using the methane synchronization, between the Vostok (low accumulation rate) and Byrd ice cores (high accumulation rate) (Blunier et al., 2004; Bender et al. 2006), although gas age shifts of up to 1000 yr were observed for some tie points. This could result from the different flow regime between Vostok, situated on a flow line, and EDC situated on a dome. At EDC, if the dome location remained stable, the total thinning is approximately linearly related to the depth of ice layers (Parrenin et al., 2007[1]). At Vostok, the thinning of ice is related to the thickness of the ice column upstream from the drilling site, where the ice originates from. As shown by Parrenin et al. (2004), differences of up to 20% in the thinning function at Vostok can be obtained depending on the scenario on the ice flow. This makes Vostok a less suitable site than EDC to constraint Δage and Δdepth based on the ice and gas chronological tie points.

The EDC Δdepth constraint provides another test of the modelled glacial Close Off Depth in Ice Equivalent (CODIE corresponding to the firn-ice transition). At the depth of the $^{10}$Be peak, the latter is roughly consistent with the empirical constraint (larger by only 3 to 4%) within its confidence interval. Δdepth is indeed the product of the CODIE by the thinning function. Assuming the thinning function has been correctly estimated, the modelled CODIE thus seems confirmed for this particular time period. Although the EDC Δdepth constraint is not very accurate (uncertainty of ~8%), this suggests that the mismatch between modelled and observed EDC Δages results from the density profile between the surface and the close-off depth, more than from the close-off depth itself.

Our findings have potentially large consequences on one of the key questions regarding climate and carbon cycle dynamics: the relative timing between Antarctic climate and $CO_2$ mixing ratio changes. Current estimates of the time relationship between the two signals at the start of the last deglaciation, based on detailed EDC measurements, point to a $CO_2$ lag of 800±600 yr compared to the $\delta$D increase (Monnin et al., 2001). This conclusion based on a Δage calculation similar to scenario 1 may have to be revisited.

The correction factor on EDC Δage that we have to apply in order to bring modelled and observed Δage into agreement at the time of the $^{10}$Be peak implies a smaller

Δage. If this correction is valid throughout the last glaciation the $CO_2$ deglacial increase may have started simultaneously or even with a lead of the $CO_2$ rise over Antarctic temperature. The consequences of such a suggestion are far beyond the scope of this paper and should certainly wait for confirmation through other time markers in the ice allowing a direct chronological fit between EDC and the Greenland ice. Furthermore $CO_2$ measurements on the EDML core with a much smaller Δage will allow estimating the timing of $CO_2$ and temperature rise with much more confidence. However, with the information at hand through our study, it is likely that the EDC Δage and therefore the $CO_2$ lag on East Antarctic temperature has also been overestimated around 18 kyr BP.

## 6 Conclusions

An improved time resolution of $CH_4$ measurements on the EDC and EDML ice cores, notably over DO #9 and 10, allowed us to evaluate the compatibility of the EDC and EDML gas chronologies. The combination of EDC-EDML gas synchronisation through $CH_4$ and ice synchronisation through volcanic horizons provides a constraint on the gas age-ice age difference at both sites. At the location of the 41 kyr $^{10}$Be event, the ice synchronisation of EDC with NorthGRIP allows us to empirically evaluate this Δage (as well as the Δdepth) for EDC and EDML.

The EDC Δage produced by the firn densification model can match our new empirical constraints only through larger accumulation rate at EDC and EDML during the last glacial period, compared with current estimates. However, it requires modification of the EDC chronology, which would change either the age of the 41 kyr $^{10}$Be event, or the modelled EDC thinning function, both of them being robust estimates. This suggests a systematic overestimate of the simulated EDC Δage during glacial periods. As a consequence, the suggested lag of $CO_2$ on Antarctic temperature at the start of the last deglaciation can be questioned and could well become a lead.

Independent estimates of paleo-accumulation rates via chemical tracers would remove the current doubt on the accumulation rate scenario. In addition, the precision of our method could be improved through direct synchronisation of a future detailed $CH_4$ record from NorthGRIP with its Antarctic counterparts. Finally, a similar study of the Japanese Dome Fuji ice core, also situated on a dome and characterized by a slightly larger accumulation rate relative to EDC, would help to better understand the physics behind the densification process on the East Antarctic plateau during glacial conditions.

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**Table 1.** $\Delta$age and $\Delta$depth estimates at EDC and EDML at the location of the $^{10}$Be sub-peaks. Definitions of depths $d_1$ and $d_2$, and ages $a_1$ and $a_2$ at NorthGRIP are given in the legend of Fig. 2. For EDML-$d_1$, the error bar represents the uncertainty in the EDC-EDML synchronisation. Ages $a_1$ and $a_2$ are on the GICC05 chronology, and the error bar on $a_1 - a_2$ is estimated as the number of uncertain layers at NorthGRIP in this time interval.

| | | (EDC or EDML)-$d_1$ | (EDC or EDML)-$d_2$ | GRIP-$d_1$ (m) | NGRIP-$d_1$ (m) | NGRIP-$d_2$ (m) | $a_1$ (yr BP) | $a_2$ (yr BP) | $a_1 - a_2$ uncer. (yr) | $\Delta$age (yr) | $\Delta$depth (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EDC | Peak 1 | 735.5±1.1 | 788.9±2 | 2231.9±1.1 | 2110.1±1.1 | 2045.9±3 | 40820 | 37410 | 190 | 3410±240 | 53.5±4.2 |
| | Peak 2 | 744.8±1.1 | 797.9±2 | 2246.2±1.1 | 2127.5±1.1 | 2063.3±6 | 41700 | 38010 | 210 | 3690±320 | 53.1±4.2 |
| EDML | Peak 1 | 1368.4±0.3 | 1393.1±1.2 | 2231.9±1.1 | 2110.1±1.1 | 2094.8±7 | 40820 | 39910 | 45 | 910±290 | 24.7±1.7 |
| | Peak 2 | 1383.3±0.4 | 1408.5±0.5 | 2246.2±1.1 | 2127.5±1.1 | 2109.8±7 | 41700 | 40810 | 35 | 890±360 | 25.1±1.3 |

**Table 2.** Depth of the methane tie points for the EDML-EDC gas synchronisation. Tie points are located at the middle of each sharp transition. The specified uncertainty (2$\sigma$) on the match has been determined as a function of depth, and then translated to ages using the EDC3 and EDML1 chronologies.

| Events | EDML depth (m) | CH4 (ppbv) | EDC depth (m) | CH4 (ppbv) | Uncertainties on the synchronisation EDML-EDC (yrs) |
|---|---|---|---|---|---|
| 1st transition (PB_YD) | 717.6 | 583.6 | 418.2 | 583.0 | 124.6 |
| 2nd transiton (YD_BO) | 766.4 | 556.3 | 442.7 | 552.2 | 172.7 |
| 3th transition (BO_LGM) | 830.2 | 532.3 | 476.1 | 532.6 | 122.3 |
| DO2 onset | 1032.9 | 369.7 | 579.9 | 373.9 | 98.4 |
| DO2 end | 1072.9 | 375.7 | 599.9 | 380.,9 | 321.3 |
| DO3 onset | 1148.0 | 405.0 | 635.4 | 404.0 | 141.1 |
| DO3 end | 1155.1 | 390.9 | 639.1 | 401.0 | 127.3 |
| DO4 onset | 1162.7 | 396.7 | 645.9 | 411.0 | 170.1 |
| DO4 end | 1174.2 | 405.7 | 651.9 | 403.7 | 56.7 |
| DO5 onset | 1224.0 | 434.5 | 681.6 | 429.8 | 196.7 |
| DO5 en | 1233.7 | 437.7 | 688.1 | 438.4 | 199.7 |
| DO6 onset | 1248.6 | 454.3 | 697.5 | 447.5 | 343.2 |
| DO6 end | 1261.1 | 454.5 | 702.1 | 450.7 | 170.,5 |
| DO7 onset | 1272.9 | 476.8 | 712.5 | 473.1 | 268.0 |
| DO7end | 1286,4 | 471.7 | 719.,7 | 472.2 | 98.0 |
| DO8 onset | 1308.5 | 484.9 | 732.0 | 488.4 | 146.4 |
| DO8 end | 1338.6 | 484.3 | 751.3 | 490.7 | 271.0 |
| DO9 peak | 1374.6 | 424.5 | 774.7 | 446.7 | 117.6 |
| DO10 onset | 1391.4 | 442.9 | 784.1 | 443.4 | 183.6 |
| DO10 end | 1404.6 | 440.5 | 790.6 | 439.8 | 183.6 |
| DO11 onset | 1416.0 | 438.1 | 801.5 | 456.9 | 75.4 |
| DO11 end | 1435.8 | 447.1 | 810.1 | 445.2 | 223.0 |
| DO12 onset | 1452.9 | 448.9 | 820.4 | 453.5 | 223.0 |
| DO12 end | 1491.3 | 458.5 | 848.1 | 465.9 | 330.0 |

**Table 3.** Comparison between the outputs of firn densification modelling scenarios and empirical constraints as derived in Sect. 3. Cf Sect. 4 for a description of the scenarios.

| Scenarios | Scenario 1 | | Scenario 2 | | Scenario 3 | | Scenario 4 | | Empirical values | |
|---|---|---|---|---|---|---|---|---|---|---|
| Drilling sites | EDC | EDML | EDC | EDML | EDC | EDML | EDC | EDML | EDC | EDML |
| Δage for both sub-peaks [yr] | 5050 | 1370 | 4820 | 1330 | 4820 | 1370 | 3970 | 1270 | 3408±240 | 909±286 |
| | 5010 | 1320 | 4800 | 1280 | 4810 | 1320 | 4020 | 1220 | 3692±315 | 892±364 |
| Differences between modelled and empirical Δage [yr] | 1650 | 460 | 1410 | 420 | 1410 | 460 | 560 | 360 | | |
| | 1320 | 430 | 1110 | 390 | 1110 | 430 | 330 | 330 | | |
| Δdepth for both sub-peaks [m] | 55.3 | 22.9 | 53.2 | 22.2 | 54.1 | 22.9 | 44.5 | 21.2 | 53.5±4.2 | 24.7±1.7 |
| | 55.0 | 22.9 | 52.6 | 22.8 | 53.5 | 22.9 | 44.3 | 21.7 | 53.1±4.2 | 25.1±1.3 |
| Differences between modelled and empirical Δdepth [m] | 1.8 | 1.8 | 0.4 | 2.6 | 0.5 | 1.8 | 9.0 | 3.6 | | |
| | 1.9 | 2.3 | 0.5 | 2.4 | 0.4 | 2.3 | 8.8 | 3.4 | | |
| Mean differences between two chronologies (EDML-EDC) [m] | 850 | | 660 | | 630 | | 30 | | | |

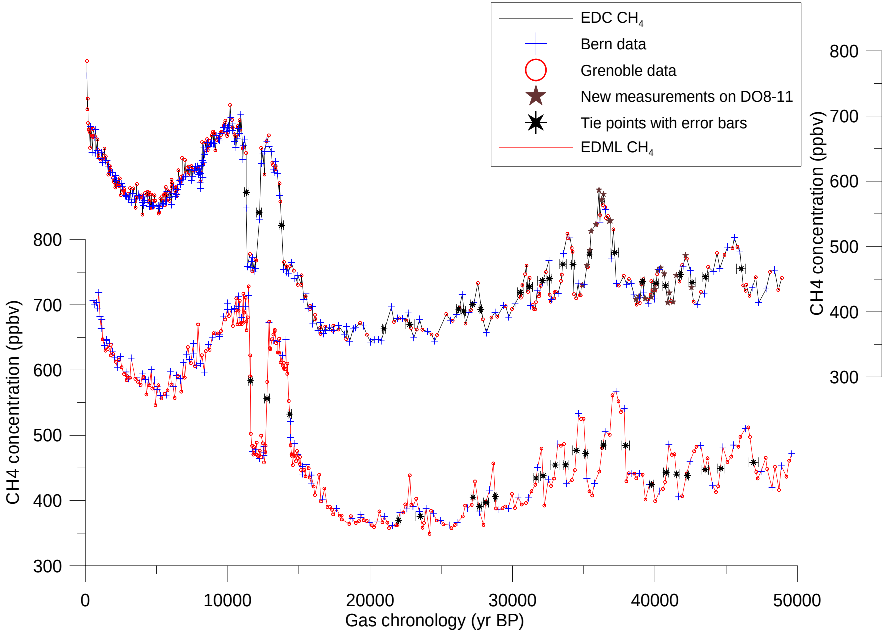

**Fig. 1.** Methane concentrations at EDML (in red) and EDC (in black) during the last 55 kyr BP. The EDC methane record consists of results published by Spahni et al. (2005) (Bern data, blue cross), new data doubling the time resolution (LGGE data, red dots) and additional new data specifically improving the time resolution between the DO #8 and #11 events (LGGE data, brown stars). The EDML methane data, already published in EPICA Community Members (2006), have been measured at LGGE and Bern. Black stars and their error bars correspond to the $CH_4$ tie points. Gas ages have been computed with the Goujon/Arnaud model (Goujon et al., 2003) according to scenario 1.

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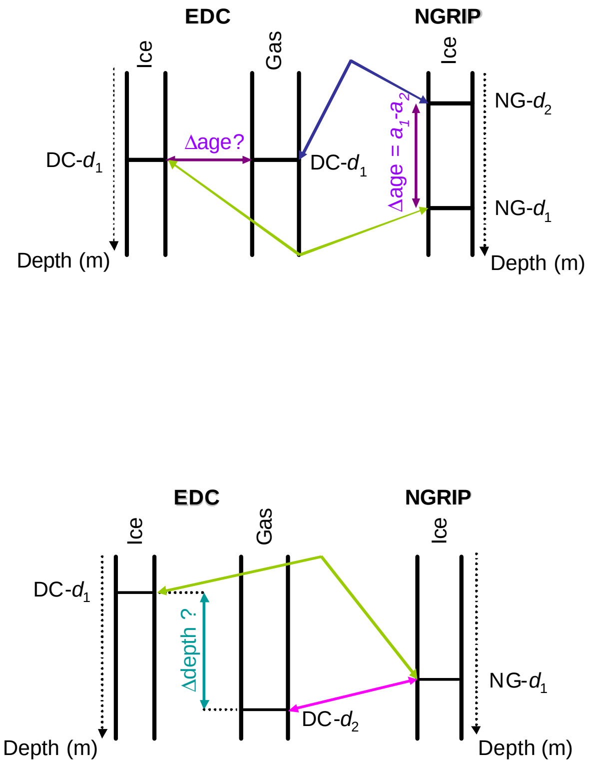

**Fig. 2.** Sketch of the Δage and Δdepth determination methods for EDC (DC). Top panel: Δage method. The green arrow represents the $^{10}$Be-$^{10}$Be tie point and the blue arrow corresponds to the methane/NorthGRIP (NG)-isotope stratigraphic link, assuming that these two records are synchronous during the rapid DO transitions (Huber et al., 2006). Bottom panel: Δdepth method. The green arrow represents the $^{10}$Be-$^{10}$Be tie point and the red arrow corresponds to the methane/NorthGRIP-isotope stratigraphic link, assuming that these two records are synchronous during the rapid DO transitions (Huber et al., 2006).

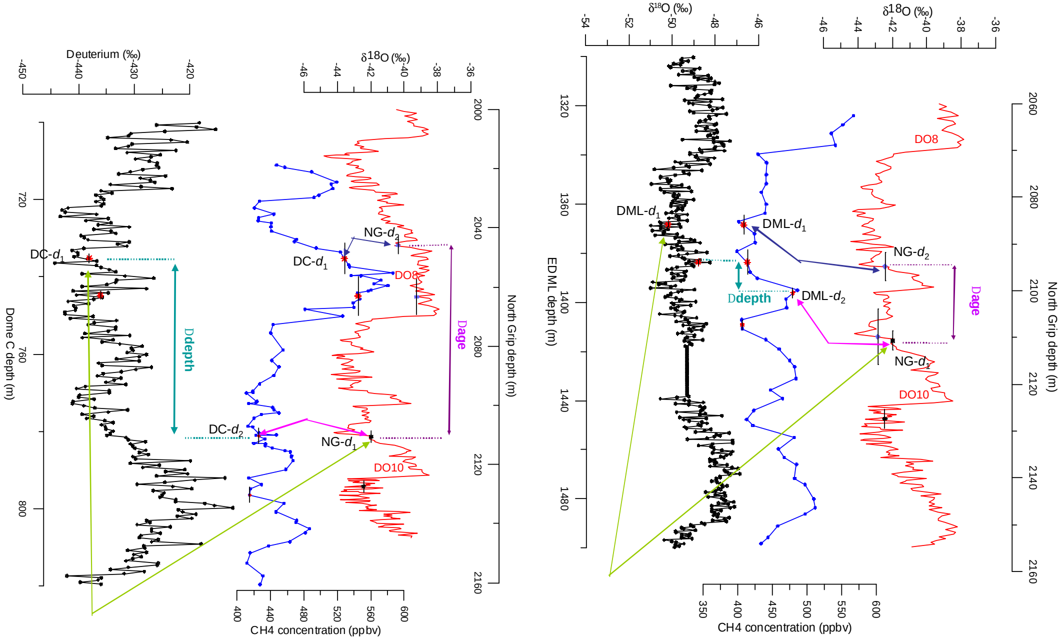

**Fig. 3.** $^{10}$Be-$^{10}$Be and methane/isotope stratigraphic links between EDC and NorthGRIP. The same method is applied for the second sub-peak. EDC deuterium data (Jouzel et al., 2007[3]) are in black. EDC methane data (this study) are in blue. NorthGRIP $\delta^{18}$O (NorthGRIP community members, 2004) is in red. Same for EDML. EDML deuterium data (EPICA Community Members, 2006) are in black. EDML methane data (this study) are in blue. NorthGRIP $\delta^{18}$O (NorthGRIP community members, 2004) is in red.

[3] Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Gallet, J.-C., Hoffmann, G., Nouet, J., Barnola, J.-M., Chappellaz, J., Fischer, H., Johnsen, S. J., Leuenberger, M., Loulergue, L., Luethi, D., Oerter, H., Parrenin, F., Raisbeck, G. M., Raynaud, D., Schwander, J., Spahni, R., Souchez, R., Selmo, E., Schilt, A., Steffensen, J. P., Stenni, B., Stauffer, B., Stocker, T. F., Tison, J.-L., Werner, M., and Wolff, E.: Orbital and millenial antarctic climate variability over the last 800 000 years, Science, submitted, 2007.

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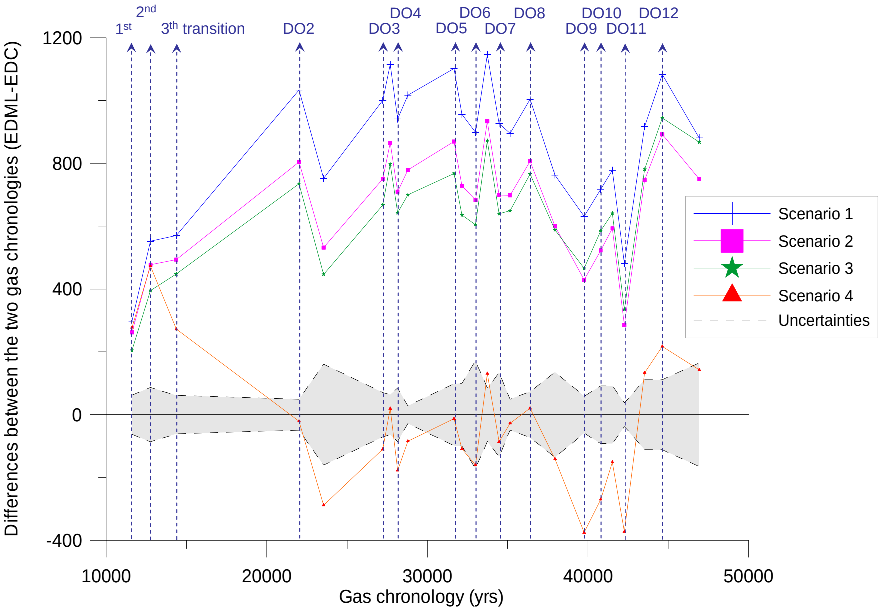

**Fig. 4.** Differences between the EDML and EDC gas chronologies for each methane tie point. The uncertainty (discontinuous line) on the methane synchronisation tie points is shown with the grey area. For a description of the scenarios, refer to Sect. 4.

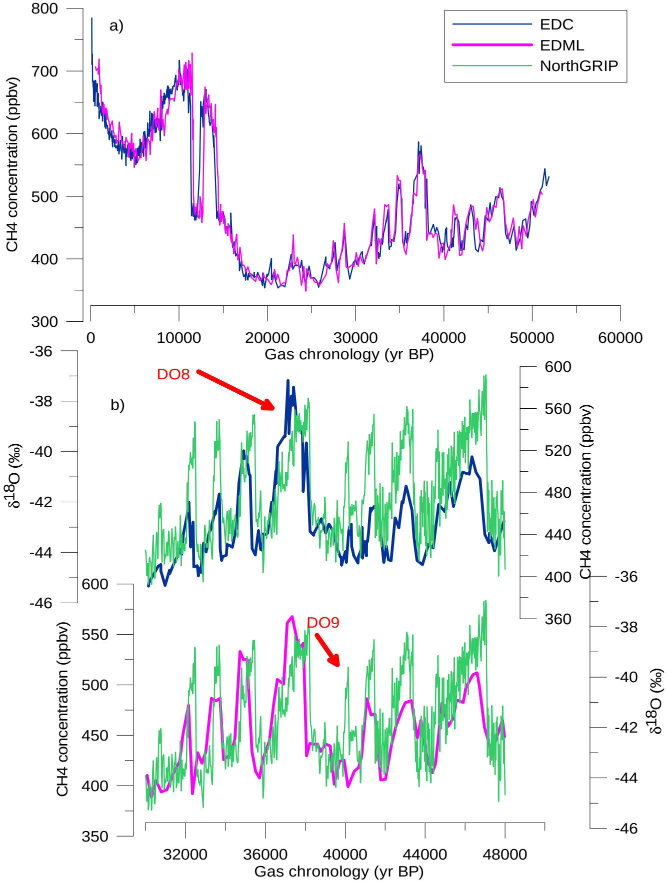

**Fig. 5.** Comparison between EDC methane (blue curve), EDML methane (pink curve) and NorthGRIP isotope (green curve). NorthGRIP age scale is GICC05. EDC and EDML gas age scales are from scenario 4 (see Sect. 4.4).