Synchronising EDML and NorthGRIP ice cores using $\delta^{18}O$ of atmospheric oxygen ($\delta^{18}O_{\text{atm}}$) and CH$_4$ measurements over MIS5 (80–123 kyr)

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Abstract
Water isotope records from the EPICA Dronning Maud Land (EDML) and the NorthGRIP ice cores have revealed a one to one coupling between Antarctic Isotope Maxima (AIM) and Greenland Dansgaard-Oeschger (DO) events back to 50 kyr. In order to explore if this north–south coupling is persistent over Marine Isotopic Stage 5 (MIS 5), a common timescale must first be constructed.

Here, we present new records of $\delta^{18}O_{\text{atm}}$ and methane (CH$_4$) measured in the air trapped in ice from the EDML (68–147 kyr) and NorthGRIP (70–123 kyr) ice cores. We demonstrate that, through the period of interest, CH$_4$ records alone are not sufficient to construct a common gas timescale between the two cores. Millennial-scale variations of $\delta^{18}O_{\text{atm}}$ are evidenced over MIS 5 both on the Antarctic and Greenland ice cores and are coupled to CH$_4$ profiles to synchronise the NorthGRIP and EDML records. They are shown to be a precious tool for ice core synchronisation.

With this new dating strategy, we produce the first continuous and accurate sequence of the north–south climatic dynamics on a common ice timescale for the last glacial inception and the first DO events of MIS 5, reducing relative dating uncertainties to an accuracy of a few centuries at the onset of DO events 24 to 20. This EDML-NorthGRIP synchronisation provides new firm evidence that the bipolar seesaw is a pervasive pattern from the beginning of the glacial period. The relationship between Antarctic warming amplitudes and their concurrent Greenland stadial duration highlights the particularity of DO event 21 and its Antarctic counterpart. Our results suggest a smaller Southern Ocean warming rate for this long DO event compared to DO events of MIS 3.

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1. Introduction

Since its discovery in Greenland ice cores (Dansgaard et al., 1984) the millennial climatic variability of the last glacial period has been increasingly documented at all latitudes (e.g. Voelker, 2002; Wang et al., 2008). Ice core records from Greenland and Antarctica have revealed the phase relationships between the Dansgaard-Oeschger events (hereafter DO events) recorded in the Northern Hemisphere and their Southern counterparts, the so-called Antarctic Isotope Maxima (AIM) (Bender et al., 1994; Jouzel et al., 1994; Blunier et al., 1998; Bender et al., 1999; Blunier and Brook, 2001; EPICA community members, 2006). The Antarctic temperature as recorded by the water isotopes increases slowly during cold Greenland stadials. This bipolar seesaw is understood to reflect the impact of the north–south heat redistribution through thermohaline circulation changes and thermal inertia of the Southern Ocean (Stocker and Johnsen, 2003; Knutti et al., 2004).

The aforementioned studies mainly concentrated on the sequence of events during MIS 2 and 3, from the middle of the last glacial period to the deglaciation, when DO events are relatively short and frequent (i.e. 17 DO events between 60 and 10 kyr). By contrast, DO events are less frequent during MIS 4 and 5 (i.e. 8 DO events between 110 and 60 kyr) and only one study presents a work going back to DO event 21 (Blunier and Brook, 2001). It is of primary importance to characterise the bipolar structure of millennial-scale variability at its onset, during the glacial inception, i.e. at a period with small ice sheet extent (~40 m sea level relative to present; Waelbroeck et al., 2002; Bintanja et al., 2005).
as well as the climate dynamics during the long DO events 19, 20 and 21 of MIS 4–5. This requires a reliable Greenland ice core record extending back to MIS 5. The recently drilled NorthGRIP ice core (75.10° N, 42.32° W, 2917 meters above sea level (m a.s.l.), 17.5 cm w. e. yr⁻¹, NorthGRIP-community-members, 2004) now provides an undisturbed record of the past 123 kyr (NorthGRIP-community-members, 2004) with the opportunity to establish an absolute timescale based on layer counting for the entire glacial period. The Greenland Ice Core Chronology (GICC05) is now available for the last 60 kyr (Svensson et al., 2008). Thanks to limited thinning, the NorthGRIP ice core provides a high resolution reference for climatic variability at the very beginning of the last glacial period including the first DO event 25.

Identifying sequences of events requires a common and precise Greenland/Antarctic ice core timescale that can be obtained through global atmospheric tracers such as isotopic composition of atmospheric oxygen, δ¹⁸O of O₂ and methane (in the following, δ¹⁸Oam and CH₄ respectively; Blunier et al., 1998; Blunier and Brook, 2001; EPICA community members, 2006; Blunier et al., 2007). The δ¹⁸Oam signal is a complex signal integrating changes of the global ice volume (Sowers et al., 1993), biosphere productivity and hydrological cycle (Bender et al., 1994; Leuenberger, 1997; Severinghaus et al., 2006; Labrèche et al., 2009; Landais et al., 2006). Arctic CH₄ concentration responds very fast to a change in the production of CH₄ and so, abrupt Greenland DO warmings are associated with sharp CH₄ rises within 50 yr (Chappellaz et al., 1993; Severinghaus et al., 1998; Flückiger et al., 2004; Huber et al., 2006). Nitrogen isotopes measured in the air trapped in the ice can be used as a complementary tool to identify the onset of DO events directly in the gas records of Greenland ice cores (Severinghaus et al., 1998; Blunier and Brook, 2001; Landais et al., 2004; Huber et al., 2006).

After an initial attempt based on the use of nitrogen and argon isotopes and limited to DO event 24 (Caillon et al., 2003), a first common dating of Antarctic (Vostok) and Greenland (NorthGRIP) ice cores over MIS 5 has been constructed using δ¹⁸Oam measured in air trapped in ice (Landais et al., 2006b). Within age scale uncertainties, DO events 23 and 24 were suggested to exhibit a north/south seesaw behaviour. This study was not fully conclusive on the DO event 25 which has no apparent counterpart in the Vostok δD profile. However, these analyses were limited by several key points. First, the north–south correlation was built through low resolution records of δ¹⁸Oam (1500 yr in Vostok) leading to large uncertainties in the determination of tie points (1000–2500 yr); second, the surface characteristics of the Vostok site (low accumulation rate – 2.2 cm water equivalent (w.e.) yr⁻¹ and temperature – − 55 °C) limit the detection of Antarctic events in the water isotopic profile despite the 100 yr resolution of the measurements (Petit et al., 1999); third, these extreme surface conditions of the Vostok site lead to a strong age difference between ice and gas at the same depth, hereafter noted Δage, reaching up to 5000 yr with a 20% uncertainty and thus contributing to a large uncertainty in the north–south synchronisation of the water isotopic records. The EPICA Dronning Maud Land (hereafter noted as EDML – S, 0.07° W, 2882 m a.s.l., 6.4 w.e. yr⁻¹, EPICA community members, 2006) ice core has been recently retrieved in the Atlantic sector of East Antarctica. Because of its relatively high accumulation rate and temperature, it allows increasing the temporal resolution with respect to Vostok. Moreover, the EDML Δage is estimated to be less than 2000 yr, i.e. 2–3 times smaller than at central Antarctic sites such as Vostok or Dome C (Loulergue et al., 2007). The current EDML ice chronology (Ruth et al., 2007) has been derived by synchronising the EDML and EPICA Dome C (EDC) ice core records on the EDC3 glaciological age scale (the EDC3 age scale is described in Parrenin et al., 2007), using volcanic horizons and dust peaks (Severi et al., 2007).

In this paper, we present in Section 2, available and new high resolution (100 yrs) records of CH₄, δ¹⁸Oam and δ¹⁵N over MIS 4 and 5 on the NorthGRIP and EDML ice cores and highlight significant millennial-scale variability in the EDML δ¹⁸Oam record. In Section 3, we describe our methodology to infer tie points between the NorthGRIP and EDML gas records from the combined measurements of CH₄ and δ¹⁸Oam. We emphasize the added value of high resolution δ¹⁸Oam records for this synchronisation. The uncertainty associated with the EDML Δage calculation is then discussed. Finally, we propose a common timescale for EDML and NorthGRIP gas records based on the EDML1 chronology as a reference (Ruth et al., 2007). We improve the accuracy of the north–south synchronisation of water isotopic records and this permit to discuss the north–south sequence of the rapid climate variability in the first part of the last glacial period (Section 4).

2. Data

2.1. CH₄ measurements

CH₄ measurements were conducted at Laboratoire de Glaciologie et Géophysique de l’Environnement (LGGE, Grenoble) and at the University of Bern. The analytical methods of CH₄ measurements are detailed in Spahni et al. (2005) and Loulergue et al. (2008). They lead to a 10-pbpv mean measurement uncertainty (Chappellaz et al., 1997). We present the first CH₄ measurements performed over the bottom part of the NorthGRIP ice core: 150 samples from the NorthGRIP ice core over the depth range 2276–3084 m (1 m depth resolution) were analysed. CH₄ concentrations vary from 757 to 450 ppbv and cover the time interval between the last glacial inception and DO event 23 (Fig. 1). Combining 160 samples analysed at LGGE with the 112 measurements conducted at Bern on the EDML ice core, the mean depth resolution is about 2 m for the EDML CH₄ record over the depth range 1828–2394 m.

Based on the official gas timescale published in Loulergue et al. (2007), the EDML CH₄ profile offers a record with mean temporal resolution of 190 yr, comparable to the 210 yr average resolution for EDC (Loulergue et al., 2008). The glacial inception is clearly visible as a steady regular CH₄ decrease from 725 ppbv to 448 ppbv as well as the fluctuations linked to DO events already shown in several Antarctic ice cores (e.g. Byrd station, Blunier et al., 1998; Blunier and Brook, 2001; EDC, Loulergue et al., 2008; Fig. 1).

2.2. δ¹⁸Oam and δ¹⁵N measured in the air trapped in the ice: analytical procedure and results

The isotopic and elementary compositions of trapped air (δ¹⁵N, δ¹⁸O, δO₂/N₂) have been measured at Laboratoire des Sciences du Climat et de l’Environnement (LSCE). To complete the high resolution NorthGRIP δ¹⁸Oam data sets published in Landais et al. (2007) and Landais et al. (2006b) over DO events 18, 19, and 20 (1–2 m resolution), DO events 23, 24 (1–2 m resolution) and 25 (3 m resolution) respectively, additional measurements were performed over DO events 21, 22 and 25 on 215 depth levels (1 m resolution). On the EDML ice core, measurements are reported from 145 depth levels between 1829 and 2426 m, i.e. covering MIS 4 and 5, with a 4 m resolution. Published δ¹⁸Oam and δ¹⁵N measurements (Landais et al., 2004, 2006b, 2007) used a manual melt refreeze air extraction technique combined with isotopic ratio measurements on a MAT 252 (Finnigan) (see Landais et al., 2003 for analytical procedure). New measurements have been performed using an automated melt extraction technique of air with water trapped at −90 °C. Samples were then analysed with a Delta V Plus (ThermoElectron Corporation) mass spectrometer. Results are reported with respect to atmospheric air. Corrections for pressure imbalance
and chemical interferences of CO₂ and δO₂/N₂ are applied to improve measurement precision (details in Severinghaus et al., 2001; Landais et al., 2003). Note that comparison of δ¹⁸Oatm measurements over DO event 25 with the two different air extraction techniques show an excellent agreement (Fig. 1b; Landais et al., 2010). Assuming this is the case for all DO events, δ¹⁵N measurements on the NorthGRIP ice core can be used to identify the onset of DO events 19, 20 and 21 in the gas phase when CH₄ measurements are missing. The grey dotted arrow around DO event 24 relates the gas and ice records at the onset of DO event 24 interstadial; the grey dotted arrow around DO event 25 shows the ambiguous identification of this event in the gas phase through the CH₄ profile as the sequence of events seems opposite to the classical δ¹⁸Oice/CH₄ relationship illustrated here with the DO event 24.

NorthGRIP raw δ¹⁸O data must be corrected for gravitational and thermal isotopic fractionations located in the firn to obtain the δ¹⁸Oatm profile following corrections procedure described in Landais et al. (2005, 2007). We only corrected EDML δ¹⁸O values for gravitational fractionation since the Antarctic counterparts of DO events are neither rapid nor large enough to induce a detectable thermal anomaly (Caillon et al., 2001).

NorthGRIP measurements of δ¹⁸Oatm have been corrected from the progressive gas loss during ice core storage (Landais et al., 2003; Severinghaus and Battle, 2006; Suwa and Bender, 2008) using δO₂/N₂ data, (for details see Landais et al., 2008). No correction for gas loss was applied on the EDML data set because values remain around –12‰, which is significantly more than the –30‰ observed for badly preserved ice (Landais et al., 2003). The final uncertainty (based on systematic duplicate measurements) is 0.06‰ for EDML δ¹⁸Oatm measurements and 0.03‰ for NorthGRIP δ¹⁸Oatm. The final δ¹⁸Oatm uncertainty is higher at EDML compared to NorthGRIP since (1) EDML δ¹⁵N duplicate measurements (unpublished data) used for gravitational signal correction of δ¹⁸O values show a stronger variability (0.02‰) than NorthGRIP δ¹⁵N measurements (0.007‰) and (2) some NorthGRIP data (less than 5%) were discarded when associated reproducibility was too large.

Given the global character of the δ¹⁸Oatm, orbital-scale variations related to precession are common to the Vostok, EDML and NorthGRIP δ¹⁸Oatm signals (Figs. 1 and 2; Bender et al., 1994; Petit et al., 1999; Shackleton, 2000; Dreyfus et al., 2007; Landais et al., 2010). Despite the absence of a timescale synchronisation, the good overlap between Vostok and EDML signals proves that the EDML ice core is undisturbed down to 2426 m depth and offers at least 149 kyr of continuous climatic history. Millennial-scale variability, already evidenced over MIS 4 (0.15‰ in 1000 yr) in the NorthGRIP ice core (Landais et al., 2007) and in Antarctica
is clearly evidenced over DO events 19 and 20 in the EDML $\delta^{18}O_{\text{atm}}$ signal. This millennial-scale variability superimposed to the long term evolution is also present over MIS 5, on DO events 21, 22, 23 and 24 for both NorthGRIP and EDML ice cores.

Fig. 1 presents a new data set of 59 duplicate measurements of $\delta^{15}N$ between 2680 m and 2710 m depth with a mean resolution of 1 m on the air trapped in the NorthGRIP ice. The $\delta^{15}N$ profile shows a rapid variation of 0.15\%\textsubscript{o} at 2694 m depth. This positive anomaly depicted in the $\delta^{15}N$ profile is the result of thermal fractionation associated with the onset of DO event 21 and is recorded 6–7 m deeper than the corresponding increase of $\delta^{18}O_{\text{ice}}$ as expected from the firnification model (Fig. 1c; Goujon et al., 2003).

3. Construction of a common timescale between EDML and NorthGRIP ice cores

3.1. Construction of a common gas timescale based on CH$_4$ and $\delta^{15}N$ profiles

We first define tie points using only CH$_4$ and $\delta^{15}N$ measurements as stratigraphic markers (Fig. 3). The sharp CH$_4$ transitions enable us to clearly define tie points between the two cores, corresponding to the mid point of each CH$_4$ sharp increase and decrease. The strong DO event 24 can be precisely constrained through tie points at the onset and at the end of this event with an uncertainty of 290 yr (procedure for error estimate is detailed in the Appendix).

DO event 21 is also clearly seen in the EDML CH$_4$ record. In the absence of CH$_4$ measurements in the NorthGRIP ice core over this time period, we used the corresponding record of $\delta^{15}N$ of nitrogen in the gas trapped in the ice since CH$_4$ and $\delta^{15}N$ increase in concert within few decades at the beginning of DO events (Fig. 1e; Severinghaus et al., 1998; Severinghaus and Brook, 1999; Flückiger et al., 2004; Huber et al., 2006; Grachev et al., 2007, 2009). This leads to a precise tie point at the onset of DO event 21 associated with a mean uncertainty of 150 yr (Fig. 3; Table 1).

Correlations are less clear for the other DO events. The CH$_4$ signature of DO events 19 and 20 is not obvious in the EDML CH$_4$ record. In the absence of CH$_4$ measurements in the NorthGRIP ice core over this time period, we used the corresponding record of $\delta^{15}N$ of nitrogen in the gas trapped in the ice since CH$_4$ and $\delta^{15}N$ increase in concert within few decades at the beginning of DO events (Fig. 1e; Severinghaus et al., 1998; Severinghaus and Brook, 1999; Flückiger et al., 2004; Huber et al., 2006; Grachev et al., 2007, 2009). This leads to a precise tie point at the onset of DO event 21 associated with a mean uncertainty of 150 yr (Fig. 3; Table 1).
The second problem is the onset of DO event 23. While the short precursor-type peak preceding the long warm phase of DO event 23 is clearly identified in the NorthGRIP record with a 150 ppbv increase, the EDML record shows a double peak with a maximum amplitude of only 50 ppbv. The small amplitude difference of this short DO event in Antarctica could be partly explained by the existence of an interhemispheric gradient that attenuates CH4 amplitude variations recorded in the Southern Hemisphere (Chappellaz et al., 1997; Dallenbach et al., 2000) and more likely by a stronger signal attenuation of fast atmospheric CH4 variations recorded in the EDML ice core due to a lower accumulation rate compared to the NorthGRIP one. In fact, the CH4 signature associated with DO events is attenuated during the enclosure processes in the ice (Spahni et al., 2003). Indeed, we estimate EDML CH4 signal attenuation almost 3 times higher than at NorthGRIP by taking into account their respective surface characteristics using the approach of Spahni et al. (2003). Finally, considering the construction of the EDC and EDML gas timescales based on CH4 records between 60 and 140 kyr (Loulergue, 2007), we reject the second peak as a precursor of the DO event 23. This would indeed imply a 1 kyr discrepancy between EDC and EDML gas age scales and, thus, contradict the firnification physics.

Third, it is tempting to identify the onset of DO event 25 as the 50 ppbv increase of CH4 at 3000 m depth in the NorthGRIP ice core and match it with the similar CH4 increase in the EDML record at 112.5 kyr. However, Fig. 1 shows that this increase in CH4 occurs at a shallower depth than the δ18Oice increase corresponding to the onset of DO event 25 in the NorthGRIP ice core. This would mean that the CH4 increase lags by several centuries the surface temperature change. Such asynchrony in the CH4 and Greenland temperature challenges the observed synchronicity between the two signals for younger events and prevents us to use confidently the corresponding EDML CH4 increase as a constraint for the onset of DO event 25.

Finally, matching EDML and NorthGRIP CH4 records over the glacial inception is not possible. Indeed, the NorthGRIP ice core does not record the whole MIS 5e period (NorthGRIP community members, 2004) so that the peak CH4 maximum cannot be identified on this ice core to provide a firm tie point. A direct matching of absolute CH4 values between Antarctic and Greenland ice cores is not possible due to expected large changes in the interglacial interhemispheric gradient.

Table 1

<table>
<thead>
<tr>
<th>NG depth (m)</th>
<th>EDML depth (m)</th>
<th>EDML age (yrs BP)</th>
<th>Gas tracers</th>
<th>Uncertainties (yrs)</th>
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<tbody>
<tr>
<td>1</td>
<td>2544.0</td>
<td>1860</td>
<td>70853</td>
<td>δ15N/CH4 (DO 19)</td>
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<tr>
<td>2</td>
<td>2552.5</td>
<td>1880.7</td>
<td>72401</td>
<td>δ18Oatm</td>
</tr>
<tr>
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<td>1902.2</td>
<td>73858</td>
<td>δ18Oatm</td>
</tr>
<tr>
<td>4</td>
<td>2586.4</td>
<td>1914.3</td>
<td>74563</td>
<td>δ15N/CH4</td>
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<tr>
<td>5</td>
<td>2667.1</td>
<td>1995.4</td>
<td>81325</td>
<td>δ18Oatm (DO 20)</td>
</tr>
<tr>
<td>6</td>
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<td>2011.6</td>
<td>82766</td>
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<tr>
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<tr>
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</tr>
<tr>
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<tr>
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<tr>
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</tr>
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</table>
Summarizing, using only CH₄ and δ¹⁵N profiles does not bring sufficient dating constraints to construct the EDML-NorthGRIP synchronisation (1) for the time interval 84–95 kyr which cover the Greenland rapid event, DO 22, and (2) prior to 108 kyr. Note, however, than when CH₄ data will become available over DO event 22 at NorthGRIP, it should enable to improve the synchronisation over the first aforementioned period.

3.2. Combining δ¹⁸O atm and CH₄ record to construct a common timescale

To complement tie points defined with CH₄ records, we identify control points (maxima, minima and mid-slopes) from δ¹⁸O atm records of NorthGRIP and EDML. In addition to the large amplitude variations linked with precession (Petit et al., 1999), we benefit from the superimposed millennial-scale variations which provide precise constraints over several DO events (Fig. 3; Table 1). As an example, over the 84–95 kyr period, the millennial-scale evolution of δ¹⁸O atm permits to define several tie points (Table 1): the long term decrease of δ¹⁸O atm accelerates strongly over the warm phase of DO event 22, followed by stable values during the stadial 21 and finally δ¹⁸O atm shows a strong decrease again during the warm phase of DO event 21.

During DO event 20, the long term δ¹⁸O atm increase is interrupted at 73.7 kyr when it remains constant until 72.4 kyr before a new long term decrease starts. The change in δ¹⁸O atm slope provides constraints over DO event 20 and confirms that the rapid 70–80 ppbv increase observed in the CH₄ record corresponds to the onset of the event. During the stadial preceding DO event 19, both NorthGRIP and EDML δ¹⁸O atm sharply increase and then decrease during the first part of the interstadial. This observation leads to the definition of an additional tie point, fully confirming the tie point suggested by the CH₄ records at 71.0 kyr.

Contrary to CH₄, δ¹⁸O atm is not affected by an interhemispheric gradient and this allows a synchronisation of the EDML and NorthGRIP δ¹⁸O atm records over the last glacial inception. Since the NorthGRIP ice core does not reach back to the δ¹⁸O atm minimum corresponding to MIS 5e, we match directly EDML and NorthGRIP δ¹⁸O atm absolute values along the glacial inception (Appendix). Supposing that a shift between the NorthGRIP and EDML δ¹⁸O atm profiles can exist after CH₄ record synchronisation as for the 105–115 kyr interval, it leads to larger uncertainties compared to time periods where CH₄ profiles are used or when δ¹⁸O atm extrema are clearly identified in the EDML and NorthGRIP records. This has been taken into account in the calculation of gas matching uncertainties (Table 1, Appendix) and in the determination of the north–south relationship over the first DO event 25 (Section 5; Table 2).

Finally, we derive a common gas chronology by using a linear interpolation of the depth levels over the 21 tie points linking the NorthGRIP gas depth to the EDML1 timescale (Table 1). This gas record synchronisation is associated with uncertainties determined by the resolution of the records and the visual choice of the tie points. For estimating the latter, ten different synchronisations have been generated using the Analyses program (Paillard et al., 1996; see the Appendix for details).

3.3. Transfer from the gas timescale to an ice timescale: Δage estimate

The ice age–gas age difference (Δage) has to be estimated for both NorthGRIP and EDML ice cores. Δage is calculated using firnification models (Herron and Langway, 1980; Barnola et al., 1991; Schwander et al., 1997; Arnaud et al., 2000; Goujon et al., 2003). These models have been empirically validated over a range of modern polar surface conditions (annual mean surface temperature between −55.5 °C and –19 °C, accumulation rates between 2.1 cm w.e.yr⁻¹ and 139.9 cm w.e.yr⁻¹).

Those firnification models can be tested using nitrogen isotopes measured in the air trapped in the ice since their fractionation only depend on physical processes in the firn. During period with no rapid temperature changes (<0.02 Kyr⁻¹), δ¹⁵N in the firm column is only affected by gravitational fractionation and brings information on the Diffusive Column Height (DCH) through the barometric equation (Craig et al., 1988; Sowers et al., 1992):

\[ \delta^{15}N = \Delta mgZ/RT \]  

where \( \Delta m \) is the mass difference between \( ^{15}N \) and \( ^{14}N \) (gm−¹), \( g \) is the gravitational acceleration (ms⁻²), \( Z \), the DCH (m), \( R \), the gas constant (J K⁻¹ mol⁻¹) and \( T \), the firm temperature (K). In Greenland, it has been shown that transient thermal gradients in the firm during the rapid surface temperature changes associated with DO events lead to additional variations of δ¹⁵N trapped in the ice through thermal fractionation (Severinghaus et al., 1998).

The NorthGRIP Δage was calculated with the firnification and heat diffusion model from Goujon et al. (2003). When forced by the variations of temperature derived from δ¹⁸O ice, the same firm densification model was shown to capture correctly the evolution of δ¹⁵N variations (Fig. 1, Landais et al., 2008). This good agreement leads to a 10% uncertainty on Δage estimate (less than 100 yr) for the NorthGRIP ice core resulting from sensitivities studies of Arnaud et al. (2000) and Goujon et al. (2003).

The EDML Δage was calculated over the last 150 kyr by running the same firn densification model (Goujon et al., 2003; Loulergue et al., 2007). Classically, the model is forced by a temperature and accumulation rate scenario (hereafter noted Scenario 1 following Loulergue et al., 2007) deduced from δ¹⁸O ice following the equations prescribed in EPICA community members (Supplementary material, 2006). The EDML glacial-interglacial surface characteristics lie within the ranges of temperature and accumulation rate of present-day studied firns. However, as for other inland Antarctic sites, a strong mismatch between measured and modelled δ¹⁵N was depicted at EDML over the deglaciation and the last glacial period (Caillon et al., 2003; Landais et al., 2006a; Capron et al., 2008). Such a mismatch casts doubts on the correct modelling of the DCH, thus on a correct estimate of Δage for the EDML ice core. We conclude that a 10% uncertainty on the EDML Δage estimate is not realistic. In the following, we will discuss three different approaches to constrain as precisely as possible the EDML Δage uncertainty, questioning temperature and accumulation scenarios as well as the firn model physics.

3.3.1. Estimate of EDML Δage uncertainties through independent markers in the gas and ice phases

Loulergue et al. (2007) evaluated their Δage estimate by using independent markers in the ice (δ¹⁸O ice and ¹⁰Be) and in the gas (CH₄) at 40.4 kyr. (Yiou et al., 1997; Guillou et al., 2004; Raisbeck et al., 2007) evaluated their Δage estimates using δ¹⁸O ice and ¹⁰Be. However, the δ¹⁸O ice record experiences a strong mismatch between measured and modelled concentrations at EDML over the deglaciation and the last glacial period (Caillon et al., 2003; Landais et al., 2006b; Capron et al., 2008). Such a mismatch casts doubts on the correct modelling of the DCH, thus on a correct estimate of Δage for the EDML ice core. We conclude that a 10% uncertainty on the EDML Δage estimate is not realistic. In the following, we will discuss three different approaches to constrain as precisely as possible the EDML Δage uncertainty, questioning temperature and accumulation scenarios as well as the firn model physics.

Table 2: Quantification of the lag between the beginning of the Antarctic temperature increase over AIM events and the onset of corresponding DO events. The associated uncertainty is also shown in Fig. 5 (grey bars).

<table>
<thead>
<tr>
<th>Phasing</th>
<th>Uncertainty (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DO/AIM 20</td>
<td>1570</td>
</tr>
<tr>
<td>DO/AIM 21</td>
<td>3360</td>
</tr>
<tr>
<td>DO/AIM 22</td>
<td>760</td>
</tr>
<tr>
<td>DO/AIM 23</td>
<td>720</td>
</tr>
<tr>
<td>DO/AIM 24</td>
<td>1500</td>
</tr>
<tr>
<td>DO/AIM 25</td>
<td>500</td>
</tr>
</tbody>
</table>

E. Capron et al. / Quaternary Science Reviews 29 (2010) 222–234
et al., 2007). They suggested that the modelled Δage at 40.4 kyr is too large by about 15%. To match the modelled and estimated Δage, Loulergue et al. (2007) ran the firn densification model with a new scenario proposing a larger accumulation rate during glacial period (defined as Scenario 4) compared to the initial accumulation estimate from δ¹⁸Oice (Scenario 1, EPICA community members, Supplementary material, 2006). If we extrapolate this method to the whole EDML timescale, we obtain a mean standard deviation between the two Δage estimates (inferred from Scenario 1 and Scenario 4, Fig. 5b) of less than 100 yr. Limits in the approach of Loulergue et al. (2007) concern several aspects: (1) they assume that the physics of firn densification in the model is correct for both sites, (2) they assume that the mismatch between EDML and EDC gas chronologies could only result from accumulation rate parameterisations. Although such approach was suitable to produce a roughly coherent gas chronology for both EPICA cores, it does not claim to provide the final answer on Δage estimates. In addition, although Δage estimates are relatively well constrained at the location of the ¹⁸¹⁸Be peak (through matching with the GICC05 timescale), their extrapolation to other depths of both sites, and in particular over MIS 4 and MIS 5, remains poorly constrained.

3.3.2. Estimate of EDML Δage uncertainties through variations of the forcing scenarios of the firnification model

The common chronology between EDML and NorthGRIP for MIS 2 and MIS 3 (EPICA community members, 2006) has a relative dating uncertainty of 400–800 yr mostly due to Δage estimate. This uncertainty has been estimated considering that the Δage uncertainty originates only from the uncertainty of the input parameters (Blunier et al., 2007). Using exactly the same approach, we show on Fig. 5b the range of possible EDML Δage, applying ±25% on accumulation (equivalent to a ±4 °C uncertainty on surface temperature) for both Scenario 1 and Scenario 4 from Loulergue et al. (2007). This estimate does not account for firmification model physics and may therefore underestimate the true Δage uncertainty.

3.3.3. Uncertainty on EDML Δage using δ¹⁵N data

Using the firmification model, the simulated δ¹⁵N is larger by 5–15% than the EDML measured values over MIS 4 and 5 (unpublished data). This clearly questions the validity of this model both for δ¹⁵N and Δage. Here, we present an alternative method to estimate Δage by using δ¹⁵N as a proxy of Lock-In-Depth (LID) (e.g. Sowers et al., 1992; Blunier et al., 2004; Bender et al., 2006). This approach enables us to discuss the phasing between the AIM and the onset of the rapid CH₄ increases (as a marker for the rapid warming of DO event in Greenland) on the EDML depth scale. The method is the following:

- First, we deduce the LID from the δ¹⁵N data points over each interval (Fig. 4) using the barometric equation (Equation (1)) and considering only gravitational fractionation. Here we have chosen to display only δ¹⁵N data corresponding to the onset of DO 21 and 24 (see caption of Fig. 4) for determining the corresponding Δdepth.
- Second, the Δdepth for a depth z (depth difference between two synchronous events) is calculated through the following equation:

  \[ \Delta \text{depth}(z) = \text{LID}(z) \times 0.7 \times T(z) \]  

Assuming that it is equivalent to the LID adjusted for compaction of the firm with a densification factor of 0.7 (Bar-Nola et al., 1991) and a thinning factor noted T, which represents the ratio between the in-situ annual layer thickness on the initial annual layer thickness. The error on Δdepth estimate arises from uncertainties on (i) the depth of the convective zone, the upper part of the firm where the well-mixed air has the same composition as the atmosphere and (ii) the thinning function. In equation (4), we have assumed that the convective zone is negligible by directly linking δ¹⁵N to the LID. Large convective zones may exist in modern Antarctic sites with very low accumulation rates and temperatures (Caillon et al., 2001; Kawamura et al., 2006). The occurrence of past convective zones was inferred from the mismatch between the LID simulated by the firmification model and the systematically smaller LID deduced from δ¹⁵N data (i.e. Caillon et al., 2001; Kawamura et al., 2006;
Landais et al., 2006a, Dreyfus et al., 2010). The maximum depth of the convective zone corresponds to a situation where the model-data mismatch is compatible with a correct Δage simulation within the range of uncertainty of the input parameters, i.e. to the situation already depicted in Section 4.3.2. Here, by assuming no convective zone at EDML, we consider an extreme case and therefore a maximum uncertainty on the Δage determination.

We first evaluate the uncertainty on the thinning function by comparing the different available estimates. First, using a 2D glaciological model, Huybrechts et al. (2007) obtained a thinning function decreasing from 0.219 to 0.176 between 2016 m and 2236 m. With an inverse method combining glaciological models with tie points constraints between the EDML and the EDC ice cores, Lemieux-Dudon et al. (2010) find a thinning function decreasing from 0.196 to 0.146 between 2000 m and 2230 m. Finally, the thinning associated to the gas dating obtained by Loulergue et al. (2007) varies from 0.194 to 0.143 in the same depth interval. This comparison gives a mean uncertainty of 15% on the thinning function at each depth of MIS 5, similar to earlier estimates (Bender et al., 2006; Parrenin et al., 2007). The Δdepth method is applied on two depth intervals: (1) 2030 m to 2016 m including the rapid CH4 increase at the onset of DO event 21 and the associated AIM (Fig. 4a) and (2) 2236 m to 2225 m including the rapid CH4 increase at the onset of DO event 24 and the associated AIM (Fig. 4b). In each case, we used the Δ15N values at the depth levels corresponding respectively to the minimum and the maximum of the rapid CH4 onset. Then, the corresponding Δdepth was deduced using the two extreme thinning values (Huybrechts et al., 2007; Loulergue et al., 2007). This Δdepth calculation permits to depict the sequence of events and especially the relative timing of rapid CH4 increase and slow Δ18Oice increase on the EDML depth scale (Fig. 4).

The last step is to compare the sequence of events obtained on a depth scale by using the Δ15N based method with the previous estimates (Sections 3.3.1 and 3.3.2). The age – depth correspondence for the EDML1 timescale is directly obtained from Ruth et al. (2007) and permits to directly visualize the phasing between the CH4 increases (i.e. Greenland warming) and the Δ18Oice increases (i.e. Antarctica warming) (Fig. 4). The comparison of the phasing between Δ18Oice and CH4 for the different scenarios shows that the uncertainty range obtained from Section 3.3.2 also encompasses the uncertainties of the Δ15N based method. Our Δdepth method provides an independent validation of our age scale and of the maximum dating uncertainties for EDML (Fig. 5b; Table 2).

4. Climatic implications

The EDML/NorthGRIP common ice timescale is displayed on Fig. 5. The total uncertainty (Fig. 5c) has been calculated by taking...
the quadratic average of uncertainties (i) of Δage for the two cores and (ii) linked with the different gas records tie points. The quantification of the exact phasing between the onsets of Antarctic warmings and rapid DO interstadials in Greenland has an accuracy of a few centuries except for the onset of DO event 25 where the total uncertainty remains higher than 1000 yr (See the Appendix).

From 80 to 123 kyr, this new synchronisation confirms the persistence of a north–south coupling with an Antarctic slow warming preceding Greenland abrupt warming by several centuries to several millennia (Table 2) and allows the extension of the Antarctic Isotope Maximum (AIM) nomenclature initially restricted to MIS 3 (EPICA community members, 2006) back to MIS 5 (Fig. 5a).

The Antarctic temperature increase associated with 5d/5c transition (106.8–108.4 kyr interval on EDML1 timescale) precedes the rapid temperature rise of DO event 24 by 1500 ± 330 yr. This robust result is well constrained by DO event 24 onset tie point inferred from the EDML and NorthGRIP CH4 profiles. This phasing is consistent with the 2 kyr (=500 yr) obtained by Caillon et al. (2003) who used the rapid CH4 increase recorded in the Vostok air as a proxies for rapid temperature change over Greenland and variations of δ18O and Δ40Ar also measured in the Vostok air as proxy for local temperature change. The good agreement between the two methods shows that even though the proxies over AIM 24 are not fully understood in Antarctic ice cores (Landais et al., 2006a), these proxies can be used to detect temperature changes in the gas record as initially proposed by Caillon et al. (2003).

We also provide a description of the north–south coupling for the DO events 20 to 23. For each event, the onset of Antarctic warming leads Greenland abrupt warming, while the maximum of the warming is concomitant at both poles. For DO events 20, 21, 22 and 23, Antarctic temperature begins to increase respectively 1.7 ± 0.3 kyr, 3.4 ± 0.2 kyr, 0.8 ± 0.6 kyr and 0.9 ± 0.5 kyr before the abrupt temperature rise in Greenland. Compared to the pioneering results of Blunier and Brook (2001) over DO event 20 and 21 (respectively lags of 1 kyr and 3.2 kyr), we confirm the asynchrony and reduce the uncertainty by more than a factor of 2. For the first time, we describe here the Antarctic counterparts AIM 22 and 25 of the small DO events 22 and 25, marked again by a lead of Antarctica with respect to Greenland for DO event 22. The north–south phasing over DO event 25 cannot however, be firmly determined because our matching uncertainty over the glacial inception is higher than 1 kyr.

MIS 5 lags (0.7–3 kyr) observed between Antarctic temperature increase and the onset of Greenland interstadials are consistent with those observed over MIS 3 (0.5–2 kyr) (EPICA community members, 2006). We confirm that peak warmth occurs in phase in Greenland and Antarctica all over MIS 5, an observation made already by Blunier and Brook (2001) back to 90 kyr. The sequence of millennial-scale climate variability between Greenland and Antarctica is therefore a pervasive characteristic from the first to the last DO event of the glacial period.

Our results thus contradict the possible existence of a critical threshold in ice sheet volume to induce climatic millennial-scale variability (McManus et al., 1999). Over MIS 3, the stadials before DO events 4, 8 and 12 are associated with major iceberg discharges respectively corresponding to Heinrich events 3, 4 and 5, respectively, whereas no such massive iceberg discharges are evidenced for MIS 5 (Heinrich, 1988; Bond et al., 1992). It challenges the straightforward link between ice volume and climate instabilities.

The bipolar seesaw mechanism is understood by changes in the heat and freshwater flux connected to the onset/collapse of the Atlantic Meridional Overturning Circulation (AMOC) and heat accumulation in the Southern Ocean (Stocker and Johnsen, 2003; Knutti et al., 2004). The evidence of a linear relationship between the warming amplitude of all AIM (inferred from the EDML δ18Oice) and the concurrent stadial duration in Greenland over MIS 3 validated this theoretical concept (EPICA community members, 2006) but the study was restricted to MIS 3 rapid events. Our new EDML-NorthGRIP timescale enables to investigate this north–south dependency over MIS 5 (Fig. 6). We limit this study to AIM 21, 23, and 24 and their accompanying stadials from NorthGRIP δ18Oice considering that our timescale synchronisation is most robust over those rapid events and that a clear seesaw pattern is identified.

Within uncertainties, DO/AIM 23 and 24 lie on the regression line established for MIS 3 rapid events (Fig. 6; EPICA community members, 2006). They are comparable with the MIS 3 largest events, DO/AIM 4, 7 and 8 and 12. This similar behaviour for events of MIS 3 and 5 shows that the Antarctic warming rate does not depend on climate background (i.e. different ice sheet volumes, greenhouse gas levels, temperature conditions and orbital configurations). This would support the use of one single characteristic timescale associated to the Southern Ocean heat reservoir to model the thermal bipolar seesaw (Stocker and Johnsen, 2003).

However, we note that AIM/DO 21 event significantly deviates from the linear regression line. The duration of the stadial prior to DO event 21 is exceptionally long (4 kyrs) and the Antarctic warming amplitude (4 °C) is the most important over the whole glacial period. This suggests that heat flow from the Southern Ocean is not constant during all AIM events and contradicts the hypothesis presented above of Stocker and Johnsen (2003) who assumed a Southern Ocean heat reservoir with only one characteristic timescale. Previous hypothesis also suggests that for long cessations of the AMOC, new temperature equilibrium in the Southern Ocean would be reached and the warming would become slower or eventually have to cease since the Southern Ocean cannot accumulate heat indefinitely (EPICA community members, 2006). However, within our age scale, the warming rate over AIM event 21
5. Summary and perspectives

- For the first time, we have combined the millennial-scale variability of both CH$_4$ and $\delta^{18}O_{atm}$ records measured at high resolution on two ice cores (EDML and NorthGRIP) to produce a common gas timescale between Greenland and Antarctica with quantified and minimal associated uncertainties over the 70–123 kyr period.

- The accuracy of the ice record synchronisation mainly depends on the $\Delta$age calculation. With a new model-independent method based on $\delta^{15}N$ measurements, we have reduced the $\Delta$age uncertainty at EDML to a few hundred years, i.e. considerably less than in central Antarctic ice cores (a thousand years).

- We have presented the first continuous north–south synchronisation for the 70–123 kyr time interval and thus extended the study of the north–south climatic asynchrony of Blunier and Brook (2001) and EPICA community members (2006) to the entire sequence of MIS 5 DO events. The onset of millennial-scale warmings in Antarctica has been shown to precede the onset of warming in Greenland by 0.7–3 kyr in agreement with the leads observed over MIS 3.

- While the bipolar seesaw is a clear feature operational from the beginning of the glacial period, the relationship between Antarctic warming amplitudes and the duration of the Greenland concurrent stadials over MIS 5 differs for DO event 21 and other DO events. This suggests variability in the oceanic circulation overturning rate between the rapid events independently of the climate background state. This deserves to be further explored with sensitivity tests run with coupled Ocean–Atmosphere models.

- Isotopic data from East Antarctic sites (Dome C, Jouzel et al., 2007; Dome F, Kawamura et al., 2007) suggest a “shoulder” in $\delta^{18}O$ or $\delta^{18}O_{ice}$ over the glacial inception as a possible counterpart to DO event 25 but the lack of a synchronisation with a Greenland record prevents a precise description of the climatic event sequence. Our synchronisation approach on EDML and NorthGRIP failed to provide a precise synchronisation of EDML and NorthGRIP around DO event 25 and its potential Antarctic counterpart. A definitive status on the set up of this interhemispheric coupling will require (i) high resolution measurements of CH$_4$ on the NorthGRIP record, (ii) a reconstruction of the local temperature signal at EDML to assess if the event recorded in the $\delta^{18}O_{ice}$ is a true climatic event considering changes in moisture origin (Stenni et al., 2010) and of surface elevation variations and ice origin changes at the EDML drilling site (EPICA community members, 2006; Huybrechts et al., 2007).

- The future NEEM deep drilling is expected to deliver a Greenland ice core older than MIS 5.4. This ice core would allow expanding the comparison of Greenland-Antarctic climate over the whole last interglacial period and Termination II.

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Appendix. Error estimate linked to our gas records synchronisation

Ice cores synchronisation through global gas records is affected by several sources of uncertainties: (i) the gas records matching and (ii) the uncertainty of $\Delta$age for the two ice cores. Section 3.3 is dedicated to point (ii). For point (i), the uncertainty depends on the resolution of the records and on visual matching biases as explained below.

1. EDML/NorthGRIP CH$_4$ matching

Sharp variations of CH$_4$ over DO events 23 and 24 recorded both in the EDML and NorthGRIP ice cores allow the identification of precise mid-slope tie points. The gas synchronisation uncertainty is therefore, only dependant on the resolution of the records. The uncertainty is calculated as the square root of the sum of squares of the EDML and NorthGRIP timescale difference (Table 1).

2. NorthGRIP $\delta^{15}N$/EDML CH$_4$ matching

Within sampling resolution, CH$_4$ and $\delta^{15}N$ have been shown to increase in concert during rapid temperature change (Severinghaus et al., 1998, Severinghaus and Brook, 1999, Huber et al., 2006, Flückiger et al., 2004, Grachev et al., 2007, 2009). Thus, as for CH$_4$ matching, the error estimate results only from the square root of the sum of squares of the $\delta^{15}N$ and CH$_4$ record time resolution. We obtain a mean $\delta^{15}N$/CH$_4$ matching uncertainty of 150 yrs at the onset of DO events 19, 20 and 21, mostly due to the EDML CH$_4$ record resolution (Table 1).

3. EDML/NorthGRIP $\delta^{18}O_{atm}$ matching

A matching via CH$_4$ records cannot be done:

(i) For the 84–102 kyr period covering the DO event 22, since no CH$_4$ measurements have yet been performed in the NorthGRIP ice core;

(ii) Over DO event 25: the non-synchronicity between abrupt temperature increase and rapid CH$_4$ variations (described in Section 3.1) prevents us from using confidently this method;
Before 110 kyr: the NorthGRIP ice core does not capture the CH$_4$ maximum corresponding to MIS 5e that is necessary to define a mid-slope tie point over the glacial inception. The interhemispheric gradient affecting CH$_4$ concentration precludes any absolute CH$_4$ levels matching.

Thus, we used $\delta^{18}$O$_{atm}$ profile synchronisation over those time periods. Millennial-scale variability superimposed on orbital-scale $\delta^{18}$O$_{atm}$ variations over DO event 22 permits to define additional markers. In general, tie points are defined at slope breaks. One exception is the bottom part (below 3000 m depth) of the NorthGRIP ice core since the corresponding $\delta^{18}$O$_{atm}$ record does not display a clear minimum at 124 kyr. The only possibility to extend the synchronisation between 110 and 124 kyr is thus to match $\delta^{18}$O$_{atm}$ absolute values which are not affecting by pole-to-pole gradient.

The relatively slow temporal variations of $\delta^{18}$O$_{atm}$ record and the low resolution associated with the EDML record make it difficult to define a systematic procedure for tie point identification. Sensitivity tests were conducted and ten different visual matchings were performed using the Analyseries program (Paillasson. Sensitivity tests were conducted and ten different visual matchings were performed using the Analyseries program (Paillasson).

Fig. A1 displays the match of the EDML and NorthGRIP $\delta^{18}$O$_{atm}$ records and its uncertainty range. This permits to visualize the result of our subjective visual matching. Over DO 19 and 20, the uncertainty is rather small because (i) we have confirmation of our $\delta^{18}$O$_{atm}$ visual matching by two CH$_4$ tie points and (ii) the resolution of the EDML $\delta^{18}$O$_{atm}$ record is relatively high (400 yrs). Over DO 22 (90 kyr), only $\delta^{18}$O$_{atm}$ matching has been used and the resulting uncertainty is about 500–1000 yrs.

Over DO events 23 and 24, where many CH$_4$ tie points are available, we observe a surprising shift between NorthGRIP and EDML $\delta^{18}$O$_{atm}$ records: NorthGRIP $\delta^{18}$O$_{atm}$ values are heavier than the EDML ones by 0.1‰. This shift is neither observed over DO events 19 to 20 nor over DO 21 where $\delta^{18}$O$_{atm}$ was also combined to CH$_4$ for the gas synchronisation. Such a shift is probably due to a problem of storage effect on the NorthGRIP $\delta^{18}$O$_{atm}$ values since $\delta^{18}$O$_{atm}$ record covering DO events 23 and 24 were performed in spring 2004 on ice stored at temperature between −15°C and −20°C while $\delta^{18}$O$_{atm}$ NorthGRIP records covering DO events 19–20 and DO event 21 were respectively measured in Spring 2002 and Summer 2007, respectively, on ice stored below −20°C.

We now discuss the uncertainty associated with the dating of the bottom part of the NorthGRIP ice core through $\delta^{18}$O$_{atm}$ only. First, the blue curve stands for the oldest dating of the NorthGRIP bottom part. Indeed, shifting the blue curve to the right means matching an increase of $\delta^{18}$O$_{atm}$ in the EDML ice core (before 124 kyr) and a decrease of $\delta^{18}$O$_{atm}$ in the NorthGRIP ice core which is impossible given the global character of this tracer. We thus consider that the shift between the red curve and the blue curve represents the maximum uncertainty on the dating and the green curve has been built as the symmetric of the blue curve with respect to the black one.

Since a shift of 0.1‰ in $\delta^{18}$O$_{atm}$ has been observed between the NorthGRIP and EDML record over the period encompassing DO events 23 and 24, it can be argued that a similar problem can affect our dating of the bottom part of the NorthGRIP ice core. However, we do not expect any gas storage effect on the NorthGRIP samples over this depth range: the first set of ice samples (low resolution) has been measured just after ice drilling hence with no storage effect detected in the O$_2$/N$_2$ ratio; the second set of samples was stored for 4 years at −25°C and did not show strong storage effect ($\delta$O$_2$/N$_2$ around −10‰). Moreover, we note that we observe a $\delta^{18}$O$_{atm}$ 0.2‰ shift between the green (or the blue) curve and the red curve so that even if such storage effect has occurred, it is included in our error bar.

Note that our age markers give a uniform evolution of age as a function of depth with less than 10% deviation from the slope deduced from the age/depth relationship of the NorthGRIP glaciological timescale (NorthGRIP c.m., 2004). Thus, our timescale built from gas age markers seems also coherent with ice flow conditions at the NorthGRIP site. The major difference is obtained at the bottom of the NorthGRIP ice core for which the glaciological timescale is not strongly constrained because of the basal melting.

Finally to estimate the total synchronisation uncertainty we added the uncertainties linked with the age determination for each ice core. The mean uncertainty is less than 400 yrs for DO events 20 to 24 but remains higher than 1000 yrs after 110 kyr (Fig. 5; Table 2).
References


