

**A brief history of ice core science over the last 50 yr**

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## Abstract

For about 50 yr, ice cores have provided a wealth of information about past climatic and environmental changes. Ice cores from Greenland, Antarctica and other glaciers, now encompass a variety of timescales. However, the longer time scales (e.g. at least back to the Last Glacial period) are covered by deep ice cores the number of which is still very limited, seven from Greenland, with only one providing an undisturbed record of a part of the Last Interglacial Period, and a dozen from Antarctica with the longest record covering the last 800 000 yr. This article aims to summarize this successful adventure initiated by a few pioneers and their teams and to review key scientific results in focusing on climate (in particular water isotopes) and climate related (e.g. greenhouse gases) reconstructions. Future research is well taken into account by the four projects defined by IPICS. However it remains a challenge to get an intact record of the Last Interglacial in Greenland and to extend the Antarctic record through the mid-Pleistocene transition, if possible back to 1.5 Myr.

## 1 Introduction

It was a great honour to be invited to give a lecture on the “History of ice core science” at the 2012 open Science Conference of IPICS, the International Partnerships in Ice Core Science. I have done it as a scientist and not as an historian using material from books such as “Frozen Annals” by Willi Dansgaard (2004), the “Two-Mile Time Machine” by Richard B. Alley (2000) and “White Planet” co-authored by Claude Lorius, Dominique Raynaud and myself, recently published by Princeton University Press (2013). My presentation was also based on a review article from Chet Langway (2008) about “The history of early polar ice cores” and from many other scientific articles, reports and websites. I have also been interested in looking at how ice core research which for about fifty years has produced such a wealth of information about past changes of our climate and of our environment, is perceived outside our scientific community; one

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well documented example is given by Spencer Weart an historian of science who has written a book “The discovery of global warming” (Weart, 2008 updated in 2013) with a chapter on Greenland ice drilling.

This review is written in the same spirit and as a scientist I am probably unable to give an unbiased account of the history of ice core science as a large part is also based on my own perception. I have started environmental research forty five years ago and, thanks to Claude Lorius, have had the opportunity to be involved in the first French deep drilling project which allowed to recover in 1978 a 905 m deep ice core at the Dome C site on the Antarctic Plateau (Lorius et al., 1979). Except for Dye 3 (Southern Greenland) and for more recent projects such as WAISCORE (West Antarctica), I have been lucky to be part of or associated with major projects conducted since the eighties in Antarctica (Vostok, EPICA Dome C and EDML, Dome F, Law Dome, Talos Dome) and Greenland (GRIP, GISP2, North GRIP and NEEM); see Fig. 1 for the location of these Greenland and Antarctic sites. My participation in field work is more limited with field seasons at GRIP, North GRIP and NEEM, but only a short visit in Antarctica.

This article deals both with the history of ice core drilling, including a brief account of ice cores recovered outside polar regions, and with ice core science. However, this would be too broad to cover all scientific aspects. Rather, I will focus on topics I am most familiar with namely climate (in particular water isotopes) or climate related (e.g. greenhouse gases) reconstructions as well as dating issues. Aspects dealing with the chemical composition of snow and ice, with the information that can be derived on past changes in atmospheric chemistry and biogeochemical cycles, with the fallout of cosmogenic isotopes, with the physics of ice, and with the modeling of ice flow and ice sheets, will not be covered.

## 2 Ice core drilling: from Camp Century to the WAIS divide ice core

As reviewed by C. Langway (2008), the first attempt to probe the interior of an ice sheet was conducted by Sorge (1935) from the study of a 15 m deep pit recovered

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at Station Eismitte (Greenland). The first ice cores were obtained about twenty years later by three separate international research teams (Langway, 2008), the Norwegian–British–Swedish Antarctic Expedition in the Queen Maud Land – now Dronning Maud Land – coast (Swithinbank, 1957; Schytt, 1958), the Juneau Ice Field Research Project in Alaska (Miller, 1954) and the Expeditions Polaires Françaises in Central Greenland (Heuberger, 1954). These ice cores drilled in the early fifties were about 100 m deep with generally low quality of ice recovery preventing detailed analytical studies (Langway, 1958) and one can mark the 1957–1958 International Geophysical Year (IGY) as the starting point of ice core research. One of the IGY priority was deep core drilling into polar ice sheets for scientific purposes. Five nations have been particularly active in the early period of deep drilling projects in polar regions – the sixties and seventies – US, Soviet Union, Denmark, Switzerland and France.

Under the leadership of Henri Bader and then of Chet Langway, US teams were very active thanks to two related US Army Corps of Engineers research laboratories: the Snow, Ice and Permafrost Research Establishment (SIPRE), and the Cold Regions Research and Engineering Laboratory (CRREL). In Greenland, two cores were drilled at Site 2 in 1956 (305 m) and 1957 (411 m) closely followed by two cores in Antarctica, at Byrd Station in 1957/1958 (309 m), and at Little America V, on the Ross Ice Shelf, in 1958/1959 (264 m). The operation moved in Camp Century in North West Greenland in the fall of 1960 and it then took a strenuous six-year field effort to recover the first-ever continuous ice core to the bedrock depth, 1388 m long (Hansen and Langway, 1966; Langway, 2008). The drillers of CRREL went on to Antarctica at Byrd Station a site of West Antarctica chosen (as Camp Century) because of its accessibility. The drilling was a success reaching 2164 m in 1968 but unfortunately the drill remained at the bottom of the hole and US drillers have had to wait until 1993 to again celebrate the success of a deep drilling.

Over this period, international partnership was established between CRREL and other US teams, with teams from the University of Copenhagen and Bern led respectively by Willi Dansgaard and Hans Oeschger. Dansgaard was a pioneer in the

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carried out a 905 m deep drilling at the inland site of Dome C (Lorius et al., 1979) in a location – which unlike Camp Century, Byrd and Vostok – was deliberately chosen on a dome where the interpretation of ice core data is in principle easier because ice at depth is formed from snow which has fallen on the site itself. Involving, teams from Grenoble, Saclay and Orsay, this core was basis for new investigations, such as measurements of beryllium 10, a cosmogenic isotope (Raisbeck et al., 1981), of carbon dioxide (Delmas et al., 1980), of  $\delta D$  and  $\delta^{18}O$  (Jouzel et al., 1982), and of the oxygen 18 of  $O_2$  (Bender et al., 1985).

Focusing on deep drillings that we define as extending beyond the Last Glacial Maximum, 20 000 yr ago (hereafter LGM), we now briefly describe the projects which have been undertaken in Greenland and Antarctica over the last thirty years. We also mention shorter cores drilled outside polar regions.

### 2.1 Deep drillings in Greenland

Both the Camp Century and the Dye 3 drilling sites (Fig. 2) were chosen for their accessibility from American bases, Thule to the northwest and Sondrestrom Fjord to the southwest. Both cores reach the last glacial period, with the discovery of a succession of abrupt climate changes but they do not provide reliable information about the last interglacial. Indeed, Dansgaard and his GISP colleagues were persuaded of the interest of drilling in the center of Greenland to cover this key period – an objective reached in Antarctica in the mid eighties thanks to the Vostok operation (Lorius et al., 1985). However, it was not simple to convince the US National Science Foundation (NSF) of the merit of such a project.

Dansgaard found an effective ally in Wally Broecker, a geochemist and oceanographer at Columbia University (New-York), who like Hans Oeschger was fascinated by the connection between the rapid variations discovered at Dye 3 and the potential changes of the ocean current in the North Atlantic (Oeschger et al., 1984, 1985; Broecker et al., 1985). In January 1987, Broecker, who was in favor of an international project between US and European teams, organised a meeting involving scientists from both sides. At



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of ~1400 m. In 1999, the international team decided to start again from the surface and a depth of 2931 m was reached in two seasons but the drilling was subsequently greatly slowed down because of “warm” ice due to high geothermal flux in this area. The drilling ended in 2003 at a depth of 3085 m in a subglacial river, the presence of liquid water in fact reducing the risk of ice flow perturbation as observed at GRIP and GISP2. As a result, North GRIP provides undisturbed climatic time series over the last 123 000 yr covering a significant part of the Last Interglacial period (North GRIP community, 2004).

Further extending the Greenland record was the objective of a drilling undertaken farther north, between North GRIP and Camp Century, at the NEEM (North Greenland Eemian ice drilling) site. New teams (Canadian, Chinese and Korean) joined the project which reached the bedrock at a depth of 2537 m in July 2010. As for GRIP and GISP2 the bottom part is perturbed by ice flow below ~2.2 km. However, available data shows that a correct time sequence can be reconstructed back to 128 500 yr ago, thus providing records over a large part of the Eemian (NEEM Community Members, 2013).

## 2.2 Deep drillings in Antarctica

In the seventies, the high ground in paleoclimate studies was indisputably held by paleoceanographers which were able to produce climatic time series covering several climatic cycles. This long records allowed Hays, Imbrie and Shackleton (1976) to establish the validity of the Milankovitch theory of ice ages. To make a significant contribution glaciologists, with no ice core extending beyond the last glacial period, must necessarily go back in time. The drilling team of the Leningrad Mining Institute, which alternated the use of thermal and electromechanical drills (Ueda and Talalay, 2007) was the first to recover ice from the previous glacial period, 150 000 yr ago (Lorius et al., 1985), thanks to very low accumulation.

At this site, where drilling was carried out throughout the year despite winter temperatures below  $-70^{\circ}\text{C}$ , the second core was completed at 950 m depth in 1972, starting from a deviation from the first hole. In case of difficulty, this technique developed by

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the soviet drillers and often used during the Vostok project (Fig. 4), allows to continue drilling without starting from the surface again. Overall, it took 12 yr between the first ice core (1970) and the recovery of previous interglacial ice on core 3G, the third core, which reached a depth of 2083 m on 11 April 1982 (Ueda and Talalay, 2007). The next day the electric generator used for the camp caught fire and the operations were suspended because the generator of the drillers was indispensable to ensure the survival of the camp.

This fire did not alter the enthusiasm of the soviet drillers. In 1984, they undertook the drilling of core 4G from the surface. In parallel, they attempted a deviation at the bottom of 3G which provided an extension down to 2200 m, a depth at which the drill was blocked and drilling in this hole definitely abandoned in November 1985. Drilling of 4G continued relatively slowly but without problems until February 1990. Again, the drill was blocked, at a deeper depth (2546 m) but still in the previous glacial period, ~ 220 000 yr ago (Jouzel et al., 1993). During the eighties, soviet drillers recovered two other cores (Ueda and Talalay, 2007): a 850 m ice core extending into the last transition at Komsomolskaïa in 1983 (Nikolaïev et al., 1988; Ciais et al., 1992) and, in 1988, a 780 m core covering the last 30 000 yr at Dome B (Jouzel et al., 1995).

The project might well have been abandoned but thanks to the Russian drillers, to the support of French and US teams, and to the heavy involvement of two scientists, Volodya Lipenkov and Jean-Robert Petit, the project went on even if it was necessary to start again from the surface at the end of 1990. A depth of 2755 m was reached in January 1994 and the core then covered two full climatic cycles (Waelbroeck et al., 1995; Jouzel et al., 1996). Then a depth of 3350 m was reached in January 1996 with an estimated age of 420 000 yr at 3310 m (Petit et al., 1999), a depth below which mixing of ice alters the climatic interpretation of the records (Raynaud et al., 2005). Close to thirty years after the operation began, core drilling was stopped in December 1998 at around 120 m above the interface with Lake Vostok. As mentioned, drilling operations have resumed and this interface was reached in February 2012.

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The success of GRIP has created a spirit of collaboration between all European partners involved and it is natural that they built a European Project for Ice Coring in Antarctica just after this success. The GRIP collaboration was extended to teams from Netherlands, Norway and Sweden, and to the Russian team of V. Lipenkov. The idea of two complementary sites in East Antarctica one at Dome C in a low accumulation area with a previous drilling operation, and one to be located in the Atlantic sector, which was then completely unexplored, so as to enable an optimal comparison with the records in Greenland. An EPICA electromechanical drill was developed based on the Danish Istuk drill and the project was launched in 1995 under my responsibility with Bernhard Stauffer as chair of the science group; these responsibilities have been taken in charge by Heinz Miller and Eric Wolff in 2002. The Dome C drilling, which benefited from the logistical support of France and Italy, began in November 1997 but the drill was stuck at a depth of 780 m after two seasons. The operations very successfully resumed at the end of 2000 and a depth of 2871 m was reached in two seasons; at this depth the retrieved climate record was already older than at Vostok (more than 500 000 yr old). The drilling conditions then became increasingly difficult; the bedrock (3260 m) was reached in January 2005 with the longest exploitable records covering slightly more than 800 000 yr (EPICA Community Members, 2004; Jouzel et al., 2007a). The second EPICA drilling logistically supported by Germany (Kohnen Station in the Dronning Maud Land sector) began in 2001 and reached the bedrock (2760 m) during the 2005–2006 field season, without noticeable difficulties. It extends, at least, in the previous glacial period (EPICA Community Members, 2006).

Another drilling project was carried out in the nineties by the Japanese team of NIPR (National Institute of Polar Research) then under the responsibility of Okitsugu Watanabe. As at Vostok, the drilling team was operating throughout the year; in the chosen site of Dome F, the depth of 2503 m (ice ~ 330 000 yr old) was reached in two years, 1995 and 1996 (Watanabe et al., 2003). Due to the drill lost, a new drilling has to be started from the surface. The bedrock (3035 m) was reached at the beginning of 2006;

this successful operation provides ice records spanning the last 720 000 yr (Kawamura et al., 2012).

During this period, US logistical support was primarily devoted to the reconstruction of the permanent base on the South Pole and to the Icecube experiment dedicated to the detection of neutrinos. US scientists concentrated on sites easily accessible from McMurdo with two drillings, at Taylor Dome (Grootes et al., 1994; Steig et al., 1998) and at Siple Dome (Gow and Engelhardt, 2000; Taylor et al., 2004), completed respectively in 1994 and 1999. Both cores gave access to ice from the last glacial period. A more ambitious drilling project, WAIS for West Antarctic Ice Sheet, has been recently carried out (between 2008 and 2011), 160 km from the location of the Byrd ice core. The bedrock has been reached at a depth of 3405 m; due to the high accumulation the core does not extend beyond the last 62 000 yr but has the advantage of providing very high resolution records.

Other teams have chosen one of the small and more easily accessible dome in the coastal regions: Law Dome (Morgan et al., 1997), Berkner Island (Mulvaney et al., 2007) and Talos Dome (Stenni et al., 2011), conducted as collaborative projects under the respective leadership of Australia, UK and Italy. Talos Dome covers a full glacial–interglacial cycle while the two other cores extends into the last glacial period; this is also the case for a shorter core (364 m) drilled on James Ross Island (Mulvaney et al., 2012). Ice from glacial periods is also accessible from near coastal sites (Yao et al., 1990) or from horizontal ice cores (Reeh et al., 2002; Dunbar et al., 2008).

### 2.3 Drillings in the Andes and the Himalaya

Lonnie Thompson (Ohio State University) was the first scientist to launch extensive ice core drilling and to believe in the scientific value of cores extracted from tropical glaciers, some of them being at risk of disappearing under the effect of global warming. With his team, he was able to circumvent the difficulties of drilling above 6000 m in developing light drills that run on solar energy and means to brought back down the ice as quickly as possible to avoid melting. Several tropical ice cores have been obtained

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that reached back this period either in the Himalayas, Dunde (Thompson et al., 1989) and Guliya (Thompson et al., 1997), or in the Andes, Huascarán (Thompson et al., 1995) and Sajama (Thompson et al., 1998). Other teams have followed on this pioneering work both in the Andes (Ramirez et al., 2003) and the Himalayas now referred to as the Third Pole (Yao et al., 2012). Although some of these cores extend back to the last glacial period, their main interest is that they are excellent archives of past El Niños (Andean glaciers) and of past monsoons (Himalayan glaciers). A presentation of associated scientific results is beyond the scope of this article as well as a comprehensive review of ice cores drilled in non-polar regions (Alps, Kilimandjaro, Russia, Alaska, Arctic regions, . . .).

### 3 Deep ice cores: what do we learn about past climate changes?

In the line of the seminal paper “Stable isotopes in precipitation” published by Willi Dansgaard (1964), climate reconstruction from ice cores has long been based on interpreting  $\delta^{18}\text{O}$  (oxygen 18) or  $\delta\text{D}$  (deuterium) profiles measured along ice cores. This approach is still extensively used but alternative methods, such as paleothermometry and the use of the isotopic composition of permanent gases ( $\delta^{15}\text{N}$  and  $\delta^{40}\text{Ar}$ ), have been developed since the nineties. Before examining the information obtained by these complementary approaches, we briefly mention the various methods used to date ice cores as summarized in Jouzel and Masson-Delmotte (2010a). Based on a recent review (Jouzel et al., 2013), we then briefly discuss how isotopic models are useful for interpreting isotopic profiles measured along ice cores, and mention the interest of combining measurements of  $\delta\text{D}$ ,  $\delta^{18}\text{O}$  and, as recently developed, of  $\delta^{17}\text{O}$ .

#### 3.1 Establishing ice core chronologies

Complementary methods are used to establish ice core chronologies. They fall into four categories: (1) layer counting, (2) glaciological modeling, (3) use of time markers and

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correlation with other dated time series, and (4) comparison with insolation changes (i.e., orbital tuning). Layer counting based on a multiparametric approach is extensively used for Greenland cores (Hammer et al., 1986; Johnsen et al., 1992; Meese et al., 1997; Alley et al., 1997; Rasmussen et al., 2006; Svensson et al., 2008) and for high accumulation Antarctic sites. It is not feasible in low accumulation areas such as Central Antarctica where other approaches must be employed. For example, the Vostok core has been initially dated combining an ice flow and an accumulation model assuming a link between accumulation and temperature (Petit et al., 1999). Orbital information contained in various time series such as methane (Ruddiman and Raymo, 2003),  $\delta^{18}\text{O}$  of atmospheric oxygen (Jouzel et al., 1996, 2002; Petit et al., 1999; Shackleton, 2000; Dreyfus et al., 2007; Bazin et al., 2013),  $\text{N}_2/\text{O}_2$  ratio in air bubbles (Bender, 2002; Kawamura et al., 2007; Suwa et al., 2008; Landais et al., 2012) and total air content (Raynaud et al., 2007) are also used. Additional dating information, either relative or absolute, is also obtained from comparison with other paleorecords (Raisbeck et al., 2007, 2008; Waelbroeck et al., 2008). The idea of an optimal use of the different sources of chronological information and of the various glaciological constraints has been exploited through an inverse modeling approach (Parrenin et al., 2001, 2004 and references therein). Inverse modeling is now of current use to provide a consistent dating of Greenland Antarctic ice cores (Lemieux-Dudon et al., 2010; Bazin et al., 2013).

At a given depth, the age of the gas is younger than the age of the ice, due to the fact that air bubbles are trapped when firn closes off at depth. The ice age–gas age difference can be estimated as a function of temperature and accumulation through firnification models (Barnola et al., 1991; Arnaud et al., 2000). The application of such models is however subject to discussion (Landais et al., 2006) and clearly contradicted by independent estimates based on alternative methods (Parrenin et al., 2013).

## 3.2 Water isotopes as indicators of past temperatures

The isotopic change measured between the LGM and the more recent period is relatively similar for ice cores from the central regions of Antarctica and Greenland with a range of  $\delta^{18}\text{O}$  variations around 5‰. This range, also observed for some near coastal sites, is larger for sites affected by significant altitude changes for LGM ice as, for example, observed at Camp Century (Dansgaard et al., 1969; Raynaud and Lorius, 1973).

The interpretation of these isotopic data is largely based on their present-day distribution characterized by a linear relationship between their annual values and the mean annual precipitation site temperature, particularly well obeyed over Greenland and Antarctica (Fig. 5). While Dansgaard and his team opted for a qualitative interpretation of  $\delta^{18}\text{O}$  profiles, Lorius and colleagues proposed quantitative estimates of associated temperature changes based on the use of this observed present-day spatial slope. This approach was first used for the old Dome C core (Lorius et al., 1979). Corrections for changes in the isotopic composition of oceanic waters, in the altitude of the ice sheet and, if necessary for the upstream origin of the ice (EPICA Community Members, 2006) are applied. With this interpretation, the four long East Antarctic isotopic records (Vostok, Dome F, EPICA Dome C and EDML) show a consistent range of  $\sim 8$  to  $10^\circ\text{C}$  between the LGM and present-day surface temperatures.

Over a longer timescale, the minimum isotopic values reached during the coldest parts of the glacial periods are remarkably similar. Instead high values can be more variable from an interglacial to the next; for example, during the last interglacial  $\delta^{18}\text{O}$  was higher than during the recent Holocene which is also true for the three previous interglacials (Petit et al., 1999; Watanabe et al., 2003; EPICA community Members, 2004; Jouzel et al., 2007a). The EPICA Dome C record illustrates a change of pacing at the time of the Mid-Brunhes event about 430 kyr BP with lower glacial–interglacial isotopic changes before this event (which is followed by an exceptionally  $\sim 28$  kyr long interglacial; EPICA Community Member, 2004).

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The most important characteristic of the Greenland records deals with the existence of rapid climatic changes during the last glacial period and the last transition (Fig. 7). These “Dansgaard–Oeschger” events (named by Wally Broecker) were discovered in the Camp Century and Dye 3 Greenland cores (Dansgaard et al., 1982, 1984). Rapid isotopic changes, often more than half of that corresponding to the glacial–interglacial difference and taking place in a few decades or even less (Steffensen et al., 2008), are followed by a slower cooling and a generally rapid return to glacial conditions. These isotopic events are accompanied by rapid changes in snow accumulation (Alley et al., 1993) and in dust fallout (Taylor et al., 1993). The existence and characteristics of these events were fully confirmed at GRIP (Dansgaard et al., 1993) and GISP2 (Grootes et al., 1993) and more recently at North GRIP (North GRIP Community Members, 2004) and NEEM (Neem Community, 2013). For Camp Century (Dansgaard et al., 1969) and Dye 3 (Dansgaard et al., 1982), the  $\delta^{18}\text{O}$  profile was used as a proxy of temperature change but only on a qualitative basis (Johnsen et al., 1972). Instead, the conventional approach was applied for GRIP (Johnsen et al., 1992) and GISP 2 (Grootes et al., 1993) leading to estimates of the LGM cooling of  $\sim 10$  to  $13^\circ\text{C}$ .

### 3.3 Alternative estimates of temperature changes in Greenland and Antarctica

It appeared rapidly that this conventional approach underestimates Greenland past temperature changes by up to a factor of 2. Such factors as the evaporative origin and the seasonality of precipitation can also affect  $\delta\text{D}$  and  $\delta^{18}\text{O}$ . If these factors change markedly under different climates, the spatial slope can no longer be taken as a reliable surrogate of the temporal slope for interpreting the isotopic signal. However, this was somewhat a surprise in our community when the interpretation of the borehole temperature profile clearly showed that the temperature increase from glacial maximum to Holocene was higher than  $20^\circ\text{C}$  and up to  $25^\circ\text{C}$  at Summit (Cuffey et al., 1995; Johnsen et al., 1995; Dahl-Jensen et al., 1998).

A new method was then developed by Severinghaus and colleagues based on the fact that air composition is very slightly modified by physical processes among them

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the gravitational and thermal fractionation. In the case of a rapid temperature change, these processes cause a detectable anomaly in the isotopic composition of nitrogen and argon which allows to infer its size. This method was applied to the rapid changes associated with the end of the Younger-Dryas (Severinghaus et al., 1996, 1998) and to the abrupt warming that led to the Bølling (Severinghaus and Brook, 1999) providing higher warming estimates ( $\sim$  up to a factor 2) than derived from ice  $\delta^{18}\text{O}$ . The abrupt warmings that marked the start of the numerous DO events during the last glacial period are also larger than initially thought (Lang et al., 1999; Schwander et al., 1997; Landais et al., 2004a,b; Huber et al., 2006; Landais, 2011; Capron et al., 2010). To sum up, all the results derived either from borehole paleothermometry or from isotopic anomalies significantly underestimate temperature changes in Central Greenland, thus seriously challenging the conventional isotopic approach. Fractionation processes occurring during firnification are now studied for other noble gases, neon, krypton and xenon (Severinghaus and Battle, 2006); due to the dependence of gas solubility on temperature, the krypton/nitrogen ratio has been used to reconstruct past mean ocean temperature (Headly and Severinghaus, 2007).

In Antarctica, both paleothermometry and the use of nitrogen and argon isotopes pose some problems due to the low accumulation and to the fact that Antarctica did not experienced abrupt temperature changes. Thus, there is no perfect alternative to calibrate the isotopic paleothermometer there. Still there are useful arguments coming from the isotopic composition of the air bubbles (Caillon et al., 2001), from constraints with respect to ice core chronologies (Parrenin et al., 2001, 2007; Blunier et al., 2004) and from paleothermometry (Salamatin et al., 1998). As reviewed by Jouzel et al. (2003), they converge towards the idea that the observed present-day spatial slope can be used to interpret Antarctic isotopic profiles with however a slight underestimation, of the order of  $\sim 10\%$ , of temperature changes.

A noticeable feature of the distribution of water isotopes is the smoothing due to the diffusion in firn and ice (Johnsen, 1977) which affects the seasonal cycle and can also erase sub-millennial variations in old ice (Pol et al., 2010). The difference in firn diffusion

of water isotopes (Johnsen et al., 2000) offers the possibility to estimate past temperature changes from very detailed  $\delta D$  and  $\delta^{18}O$  profiles in ice cores (Simonsen et al., 2011). Co-istopic measurements ( $\delta D$  and  $\delta^{18}O$ ) have been also applied to study basal ice as a result of the fractionation processes taking place during melting/refreezing processes (Jouzel and Souchez, 1982; Souchez and Jouzel, 1984; Jouzel et al., 1999).

### 3.4 The contribution of isotopic models

The  $\delta D$  and  $\delta^{18}O$  of snow have long been the unique tool for reconstructing past temperatures in polar regions; these parameters are still the basis of climate reconstruction from ice cores as they provide continuous, and potentially high resolution, records. In turn, the ice core community has a long tradition in the modeling of these isotopes which have been incorporated into a hierarchy of models. While the dynamically simple Rayleigh model applied by Dansgaard (1964) has been extended to account for kinetic fractionation processes taking place from the oceanic surface to polar regions (Merlivat and Jouzel, 1979; Jouzel and Merlivat, 1984; Ciais and Jouzel, 1994), water isotopes have been implemented in atmospheric General Circulation Models (IGCMs) which allow to account for the dynamical complexity of the Earth atmosphere.

After the pioneering work of Joussaume et al. (1984) using the LMD GCM,  $\delta D$  and  $\delta^{18}O$  have been implemented in the GISS (Jouzel et al., 1987a) and ECHAM (Hoffmann and Heimann, 1993) models. Since these early IGCMs there has been an increasing interest for this approach with currently a dozen of modeling groups involved (Jouzel, 2013). Their increased spatial resolution clearly improves the data-model intercomparison at a regional scale (Fig. 8). Such models allow a direct comparison between spatial and temporal slopes by simulating different climatic periods. Using the ECHAM model, Werner et al. (2000) convincingly explained the observed discrepancy between borehole and isotope temperatures in Greenland. Instead, this same model (Hoffmann et al., 1998; Jouzel et al., 2007b), indicates that in central Antarctica the temporal slope is close to its modern spatial analogue (Fig. 8) justifying the use of present-day observations to interpret paleodata. As fully discussed in Jouzel (2013),

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more recent simulations (Lee et al., 2008; Sime et al., 2008, 2009; Risi et al., 2010) do not fully support this conclusion. In particular, Sime et al. (2008, 2009) have pointed out that using present-day observations underestimates (again of up to a factor of ~two) temperature changes for warmer than present-day climates in Antarctica, which may also hold true for Greenland (Risi et al., 2013).

### 3.5 Combining information from $\delta D$ , $\delta^{18}O$ and $\delta^{17}O$

At a global scale, precipitation  $\delta D$  and  $\delta^{18}O$  are linearly related to each other throughout the world with a slope of about 8 (Craig, 1961) and a deuterium excess, hereafter the d-excess, defined as  $d = \delta D - 8 \cdot \delta^{18}O$ , of about 10‰ (Dansgaard, 1964). Early ice core isotopic studies were based on the analysis of either  $\delta^{18}O$  (Dansgaard et al., 1969, 1982; Epstein et al., 1970; Johnsen et al., 1972) or  $\delta D$  (Lorius et al., 1979) which independently provide access to past temperature changes. Due their close linear relationship, it was thought that measuring both isotopes would not bring additional climatic information, until the work of Merlivat and Jouzel (1979) showing that the d-excess of a precipitation is influenced by the conditions prevailing in the oceanic moisture source region (temperature, relative humidity and, to a lesser degree, windspeed). This link has further been confirmed for polar snow (Johnsen et al., 1989; Petit et al., 1991; Ciais and Jouzel, 1994); its use for extracting information about moisture sources has been developed in the eighties (Jouzel et al., 1982; White et al., 1988; Johnsen et al., 1989). Since then,  $\delta D$  and  $\delta^{18}O$  are quite systematically measured in order to provide such additional information both from ice cores drilled in Antarctica (Jouzel et al., 1982; Vimeux et al., 1999, 2002; Cuffey and Vimeux, 2001; Stenni et al., 2001, 2003, 2010; Uemura et al., 2004, 2012) and Greenland (Masson-Delmotte et al., 2005; Jouzel et al., 2007b; Steffenssen et al., 2008).

In contrast, it is only recently that measurements of the triple isotopic composition of water has found applications in paleoclimatology (Landais et al., 2008; Winkler et al., 2012). Combining deuterium, oxygen 18 and oxygen 17 measurements in ice cores is promising for getting access to variations of both average temperature and relative

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contributed to the extension of the CO<sub>2</sub> record over the last 800 000 yr (Siegenthaler et al., 2005; Luthi et al., 2008). The change of pacing characterized by less warm interglacials for the earlier period (Jouzel et al., 2007a) is accompanied by a parallel change in CO<sub>2</sub> which makes that the relationship between this greenhouse and climate is truly impressive (Fig. 9).

The same type of correlation – lower concentration during glacial periods than during interglacials – is observed for CH<sub>4</sub> and N<sub>2</sub>O (Fig. 9) two greenhouse gases which show also significant increases due to human activity. Analysis of CH<sub>4</sub> has been developed by the Bern team (Stauffer et al., 1985) and by the Grenoble team (Raynaud et al., 1988). Between the LGM and the preindustrial period, a doubling or so of CH<sub>4</sub> has been documented (Stauffer et al., 1988). N<sub>2</sub>O also increases between these two periods (Zardini et al., 1989; Leuenberger and Siegenthaler, 1992; Sowers et al., 2001) and shows variations during abrupt climate changes (Fluckiger et al., 1999). Obtained by Chappellaz et al. (1990), the CH<sub>4</sub> record covering the last glacial–interglacial cycle reveals a close correlation with temperature changes and appears also influenced by monsoonal activity. It has been extended to the entire Vostok core (Petit et al., 1999) and more recently to the last 800 000 yr showing, as for CO<sub>2</sub>, lower interglacial values for the earlier period (Delmotte et al., 2004; Spahni et al., 2005; Loulergue et al., 2008). Greenland ice cores revealed another very interesting feature of the CH<sub>4</sub> record, namely its close link with the rapid temperature warming associated with DO events (Chappellaz et al., 1993; Brook et al., 1996) and with rapid changes occurring during the last deglaciation (Severinghaus and Brook, 1999); we note here that reliable CO<sub>2</sub> measurements are not accessible on Greenland ice due their highest level of impurities. The N<sub>2</sub>O Antarctic record shows also glacial–interglacial changes but is disturbed by artifacts linked with elevated dust concentration (Sowers et al., 2006; Spahni et al., 2005; Schilt et al., 2009). Ice core data on more recent periods prove extremely useful to document the increases in CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O over the last two centuries (MacFarling Meure et al., 2006).

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For CO<sub>2</sub>, natural variations imply the circulation of the oceans and their productivity and, to a certain degree, interactions with the continental biosphere. On the contrary, variations in CH<sub>4</sub> essentially come from the impact of the climate on its earthly sources, including swamp zones and perhaps the frozen ground of high northern latitudes. Isotopic measurements, which need to be extremely precise, have allowed to shed light on the mechanisms involved. This includes <sup>13</sup>C in CO<sub>2</sub> (Leuenberger et al., 1992; Indermuhle et al., 1999; Elsig et al., 2009; Lourantou et al., 2010; Schmitt et al., 2012) and <sup>13</sup>C (Ferretti et al., 2005; Schaefer et al., 2006; Fischer et al., 2008) and δD (Bock et al., 2010) in methane. These results have been completed by biogeochemical modeling aiming to account both to the changes in concentrations and isotopic composition (Kohler et al., 2010; Bouttes et al., 2011). In relation with the CO<sub>2</sub> cycle, the oxygen 17 composition of entrapped air bubbles has been measured over the last 60 000 yr allowing to estimate the biologic oxygen productivity (Blunier et al., 2002). The isotopic composition of N<sub>2</sub>O (<sup>15</sup>N and <sup>18</sup>O) proves also interesting for a better understanding of processes at the origin of atmospheric variations and of the artefacts recorded in ice cores (Sowers et al., 2001). Many other gaseous species as CO (Haan et al., 1996, 1998), COS (Sturges et al., 2001a), various chlorine, bromine and iodide and other species of interest for atmospheric chemistry (Sturges et al., 2001b; Reeves et al., 2005) have also been measured in firn and ice.

The Vostok data published in the eighties and nineties led to the idea that the variations in greenhouse gases have played an important climatic role in the past as amplifiers vis-à-vis changes in insolation (Genthon et al., 1987; Lorius et al., 1990; Jouzel et al., 1993; Petit et al., 1999). Further confirmed by the extension of the CO<sub>2</sub> and CH<sub>4</sub> records to the last 800 000 yr, this interpretation – which was already taken as a clear illustration of the climatic role of CO<sub>2</sub> at the time of the launching of the Intergovernmental Panel on Climate Change (1988) – is fully supported by climate models. At the glacial-interglacial timescale, the natural variations in concentrations of CO<sub>2</sub> and CH<sub>4</sub> is equivalent of that linked to human activity during the last two hundred years. The correlation between the greenhouse effect associated with these two gases led Lorius

et al. (1990) to propose an estimate of the climate sensitivity (e.g. for CO<sub>2</sub> doubling) based on paleodata. They inferred a range of ~ 3 to 4 °C in broad agreement with currently cited value (2 to 4.5 °C as in IPCC, 2007).

The approach followed by Lorius et al. (1990) did not require that the complexity of the mechanisms of glacial–interglacial climatic changes be completely deciphered or that a definitive response to the “chicken or egg” question be answered: which is the cause, which is the effect? Indeed, there is a difficulty to determine precisely the timing between greenhouse and climate changes because of the uncertainty associated with the difference between the age of the gas, estimated from a firnification model (Barnola et al., 1991), and the age of the ice; at low accumulation sites such as Vostok, this uncertainty can be higher than 1000 yr (Petit et al., 1999). Based on this approach, two studies pointed out to a lead of Antarctic warming with respect to the CO<sub>2</sub> increase during the last 3 terminations (Fischer et al., 1999; Monnin et al., 2001). Caillon et al. (2003) confirmed this result for termination III from a completely different method based on the surprising similarity between the  $\delta D$  (or  $\delta^{18}O$ ) of ice and the isotopic composition of argon – then taken a proxy of climate change in the gas phase. However, the existence of such a lead is now challenged from a third method: using the air  $\delta^{15}N$  to determine the depth at which air in the ice is permanently trapped, Parrenin et al. (2013) concluded that Antarctic temperature did not began to rise before CO<sub>2</sub> during termination I.

Other properties are recorded in the entrapped air bubbles. In collaboration with French colleagues, Michael Bender pioneered the measurement oxygen 18 of O<sub>2</sub> focusing on the last deglaciation (Bender et al., 1985). This parameter is influenced by the productivity of the continental and oceanic biosphere and by the  $\delta^{18}O$  of continental and oceanic waters, and thus sea-level change (Bender et al., 1994a; Sowers et al., 1991; Malaizé et al., 1999; Jouzel et al., 1996; Severinghaus et al., 2009; Landais et al., 2010). The extension of this record (Jouzel et al., 1996; Petit et al., 1999; Kawamura et al., 2007; Dreyfus et al., 2007; Landais et al., 2010) pointed out to the influence of insolation changes with the presence of a strong precessional cycle which has been

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used to place chronological constraints on chronologies of Vostok, Dome F and EPICA Dome C cores. Bender was also at the origin of the discovery of a link between small measured variations of the  $N_2/O_2$  ratio and insolation changes (Bender, 2002). Although not fully understood, these variations which are linked with the firnification process, are now extensively used for dating purposes (Kawamura et al., 2007, 2012; Suwa and Bender, 2008; Landais et al., 2012). The same applies for the record of total gas content; beyond being influenced by the air pressure and thus the altitude of the ice sheet (Raynaud and Lorius, 1973; Vinther et al., 2009), the obliquity cycle is clearly imprinted in the glacial–interglacial record (Raynaud et al., 2007; Lipenkov et al., 2011).

Understanding the link between isotopic records from both polar regions became a topic of interest in the nineties (Jouzel et al., 1994b; Bender et al., 1994b). Establishing this link has considerably benefited from measurements of properties such as  $\delta^{18}O$  of  $O_2$  and methane concentration which should show similar variations in air entrapped either in Greenland or in Antarctic ice, except for the existence of a small inter-polar  $CH_4$  gradient (Dallenbach et al., 2000). This approach has first been applied using slow changes of  $\delta^{18}O$  of  $O_2$  (Bender et al., 1994b, 1999) and then developed using well defined methane variations (Blunier et al., 1998; Blunier and Brook, 2001; Morgan et al., 2002). This allowed to correlate Greenland and Antarctic records showing that abrupt Greenland events have smooth counterparts in Antarctica with in general the onset of isotopic changes preceding the onset in Greenland by 1500 to 3000 yr whereas their maxima are apparently coincident. This one-to-one coupling (EPICA Community Members, 2006) which supports the bipolar seesaw hypothesis (Broecker, 1998; Stocker and Johnsen, 2003) has been fully confirmed from the comparison of the  $\delta^{18}O$  records obtained along the North GRIP and EDML cores (Fig. 10). Note that recent studies have also demonstrated the possibility to directly and closely correlate ice records from Greenland and Antarctica, at least for some specific time periods. This is done using either the well defined beryllium 10 peak around 41 000 yr ago (Raisbeck et al., 2007) or easily identifiable volcanic events (Svensson et al., 2013) and allows to test the reliability of gas age–ice age estimates.

## 5 Future challenges

Thanks to pioneers who initiated ice core drilling in Greenland, Antarctica and in non-polar glaciers, to their scientific and technical teams, to the continuous development of drills and to their successful deployment, to the logistical and financial support of numerous organisations, to international collaborations and to its capacity to continuously attract young scientists, the ice core community can be proud of what has been achieved and produced since the first deep drilling which allowed to recover ice from the last glacial period (1966 at Camp Century). This applies to the topics on which we have focussed (mainly climate and atmospheric composition) and holds equally true for the aspects we have not covered (atmospheric chemistry, biogeochemical cycles, cosmogenic isotopes, physics of ice, modeling of ice sheets, ...). Beyond shedding light on past changes, ice cores provide a lot of information relevant to future climate change, with the discovery, in Antarctica, of a strong link between greenhouse gases and climate over the last 800 000 yr and of rapid and abrupt climate changes in Greenland. They allow to document past climate variability at various time scales, contribute to establish the links between climate changes in Northern and Southern Hemisphere. They are unique in that they provide access to past climate forcings. This includes greenhouse gases but also solar (from cosmogenic isotopes) and volcanic and other aerosols forcings (from the chemical composition of the ice) allowing to test the sensitivity of climate models and their ability to identify the contribution of human activities to recent climate change.

Future challenges in ice core research are well taken into account by the four projects defined by IPICS (Brook et al., 2006): (1) to get a 1.5 million year record of climate and greenhouse gases from Antarctica, (2) to cover the Last Interglacial and beyond in Greenland, (3) to build a network of bipolar ice core records spanning the past 40 000 yr and (4) to get ultra high resolution records of climate variability and climate forcings spanning the past 2000 yr. Projects dealing with the latter objectives (2000 and 40 000 yr) have developed since the launching of the IPICS initiative but after the

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drilling of NEEM, it appears more challenging that initially thought to get an undisturbed ice core reaching back the previous glacial period in Greenland.

The case for extending the ice core record to 1.5 Myr, very well established by the IPICS initiative (IPICS, 2008), is indeed reinforced by results recently published by the deep-sea core community. For the oldest half of this period, we are mainly reliant on marine sediment records which allow to depict the transition from a 40 kyr world to a world dominated by a 100 kyr cyclicity, and point to a shift corresponding to the start the Mid-Pleistocene Transition (MPT) 1.25 Myr ago. Despite rapid progresses in the reconstruction of past atmospheric CO<sub>2</sub> concentration from various proxies in terrestrial and marine archives, there is still a need for a direct and detailed determination from air bubbles trapped in ice cores (Jouzel and Masson-Delmotte, 2010b). In this scientifically very exciting context, the major challenge of the ice core community concerns the selection of the best possible drilling site to obtain an undisturbed record covering the last 1.5 Myr in Antarctica. High resolution cartographies, radar mapping as well as high resolution modeling will be needed. Because of the logistical costs to set up a new base in remote places in central Antarctica, new rapid reconnaissance technologies can be envisaged to qualify the chosen drilling site at low cost (Severinghaus et al., 2010). For example, an innovative instrument combining a drill and a probe in currently developed under the leadership of Jérôme Chappellaz; it would allow, within one field season, to drill down through 3 km of ice and measure at the same time key parameters such as water isotopic composition and greenhouse gas composition. Such a technology would also provide preliminary climate information prior to the heavy deep drilling operations. Given its high expected outcome, the opportunity of new technological breakthroughs and the ongoing international collaborative effort of the ice core community under IPICS, one should be optimistic on the recovery of one, or better several, very old Antarctic ice cores spanning through the MPT transition, in the coming years.

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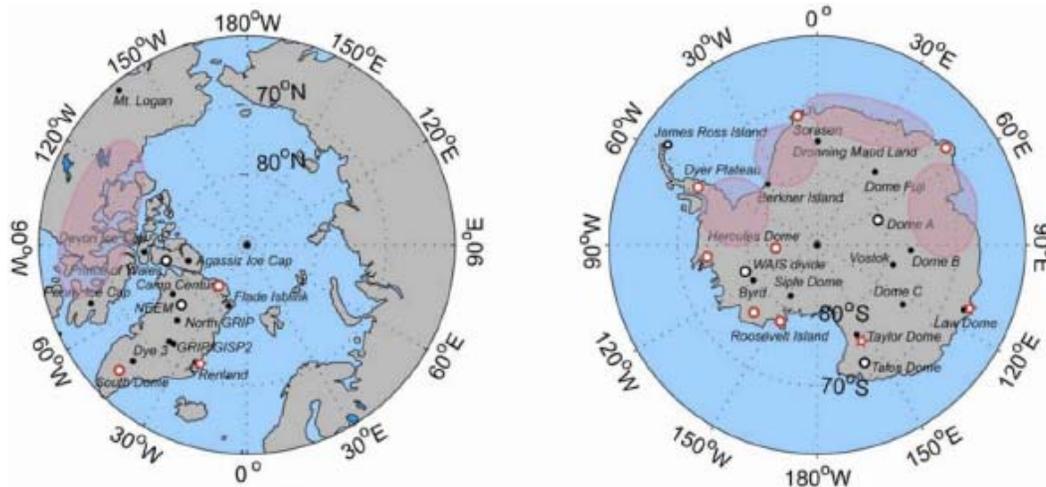
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**Fig. 1.** Greenland and Antarctic deep drilling sites synthesised for the International Partnership for Ice Core Science (from <http://www.pages-igbp.org/ipics/>).

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**Fig. 2.** Some pioneers of ice core research: left: Willi Dansgaard, Chet Langway and Hans Oeschger (from left to right); upper right: Claude Lorius; lower right: Lonnie Thompson.

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**Fig. 3.** The science trench at NEEM.

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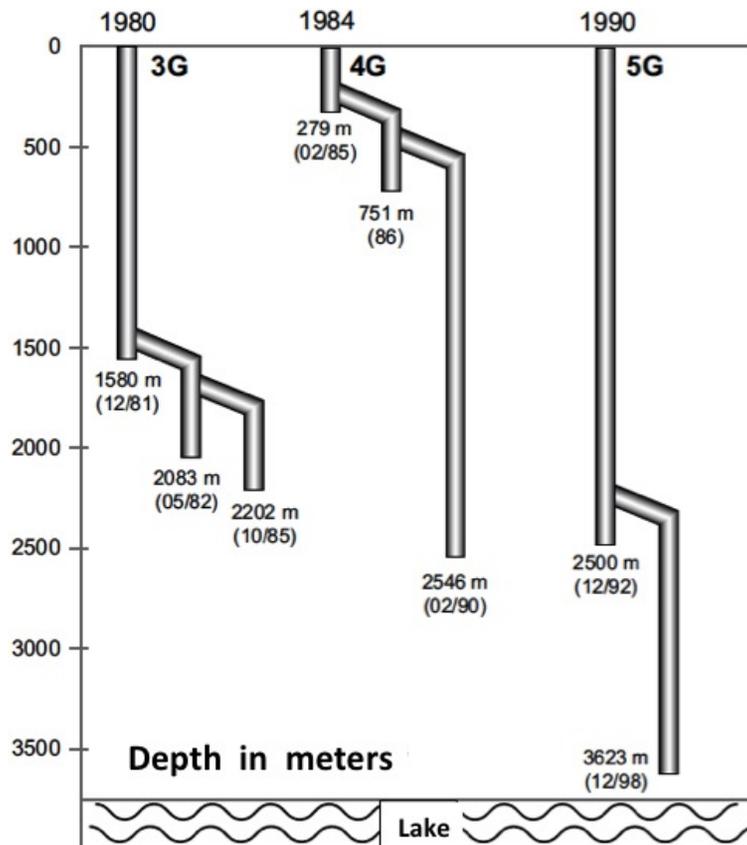


Fig. 4. Deep drillings at the Vostok site.

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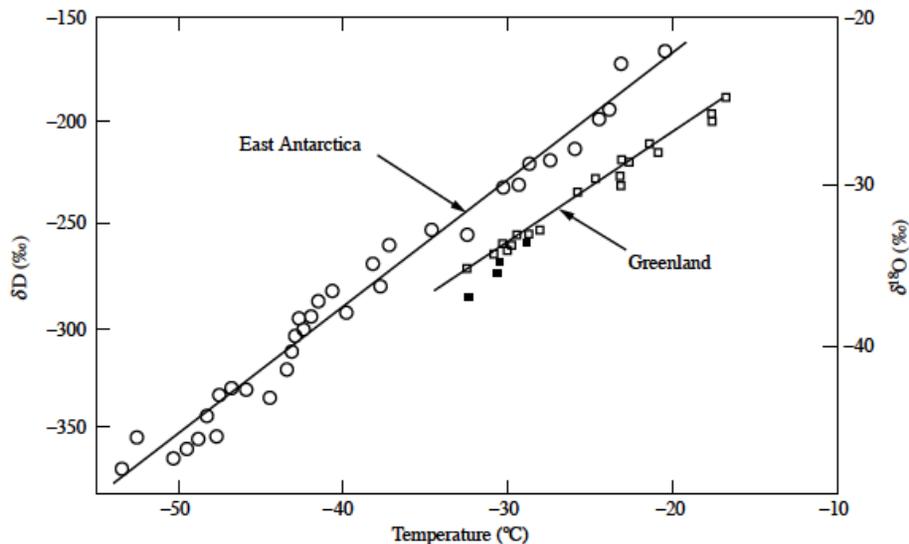
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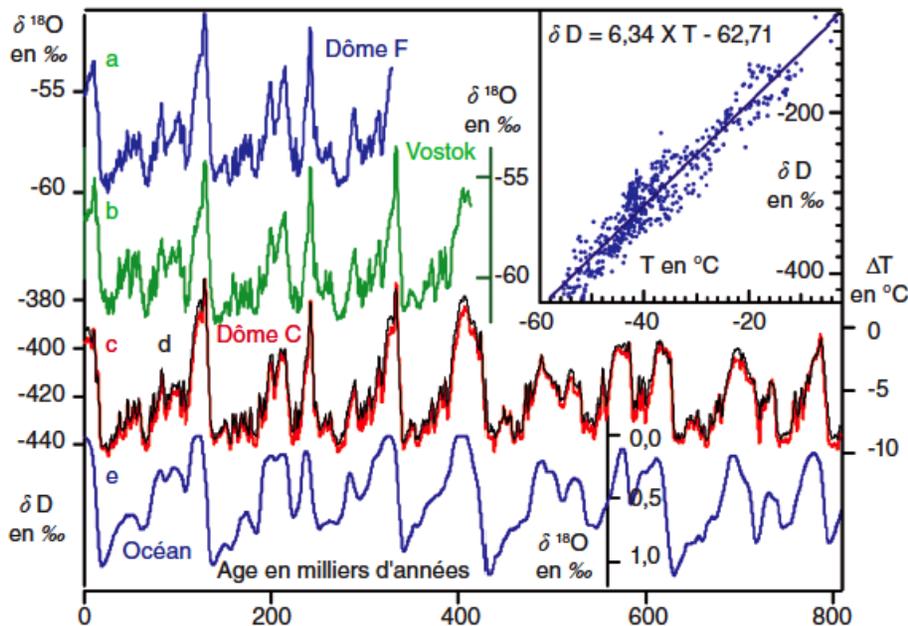


**Fig. 5.** Isotope content of snow versus local temperature (annual average). Antarctic data ( $\delta\text{D}$ , left scale) are from Lorius and Merlivat (1977) and Greenland data ( $\delta^{18}\text{O}$ , right scale) are from Johnsen et al. (1989).

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**Fig. 6.** Stable isotope records from deep Antarctic ice cores: Dome F (Watanabe et al., 2003), Vostok (Petit et al., 1999) and Dome C (Jouzel et al., 2007) with in addition the Dome C temperature (red curve, temperature scale on the right) estimated using the conventional approach (based on the use of the spatial slope, see insert adapted from Masson-Delmotte et al., 2008) as a surrogate of the temporal slope. The oceanic record adapted from Lisiecki and Raymo (2005) is used as a proxy of sea-level change.

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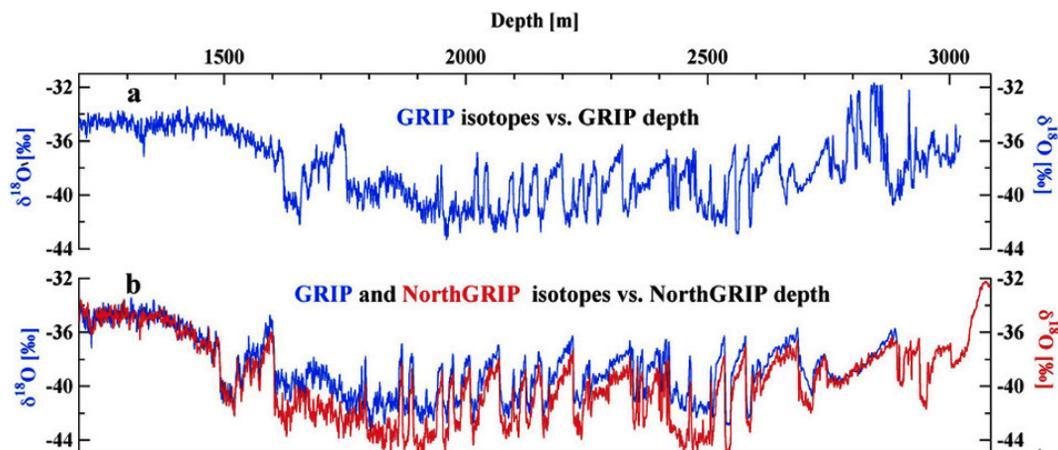
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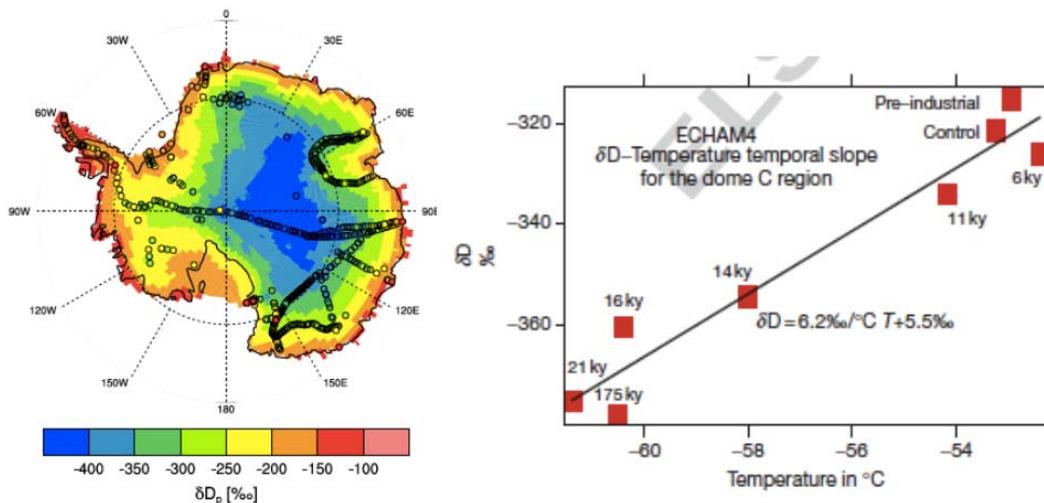


**Fig. 7.** (a) The GRIP (blue) and (b) NGRIP (red) oxygen isotopic profiles with respect to depth. For comparison, the GRIP record (blue) has been plotted on the NGRIP depth scale using the rapid transitions as tie points (adapted from North GReenland Ice core Project members, 2004).

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**Fig. 8.** Left panel: observed (colored circles from a compilation by Masson-Delmotte et al., 2008) and simulated (ECHAM5-wiso with a fine spatial T159L31) annual mean HDO values in precipitation ( $\delta D_p$ ) for Antarctica (after Werner et al., 2011). Right panel: the temporal slope as derived from ECHAM 5 IGCM for the Dome C region (Jouzel et al., 2007b).

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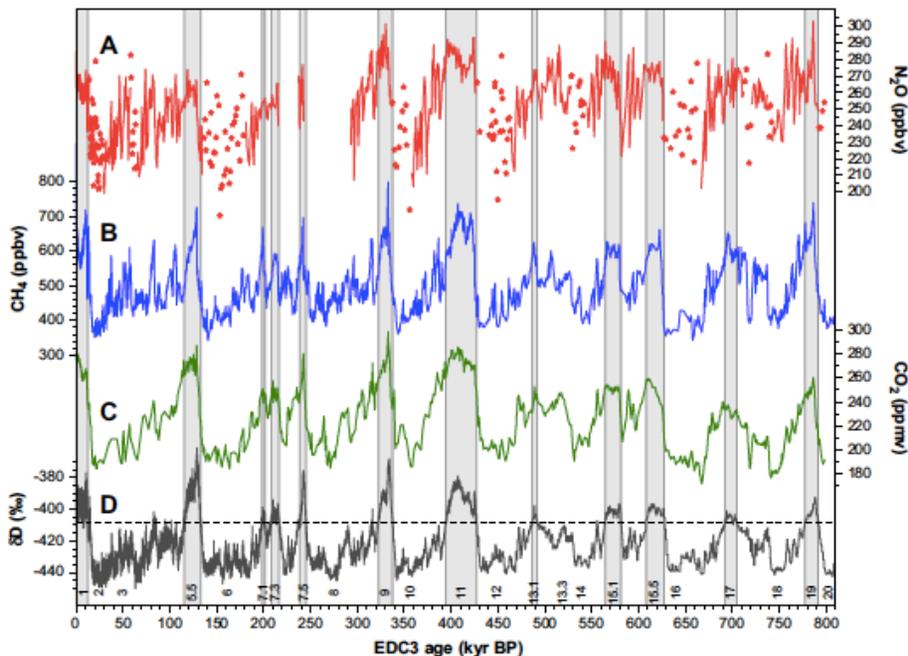
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**Fig. 9.** Variations, over the last 800 000 yr, of deuterium ( $\delta D$ ; black), a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases  $CO_2$  (green),  $CH_4$  (blue), and nitrous oxide ( $N_2O$ ; red) derived from air trapped within ice cores from Antarctica (Schilt et al., 2009).

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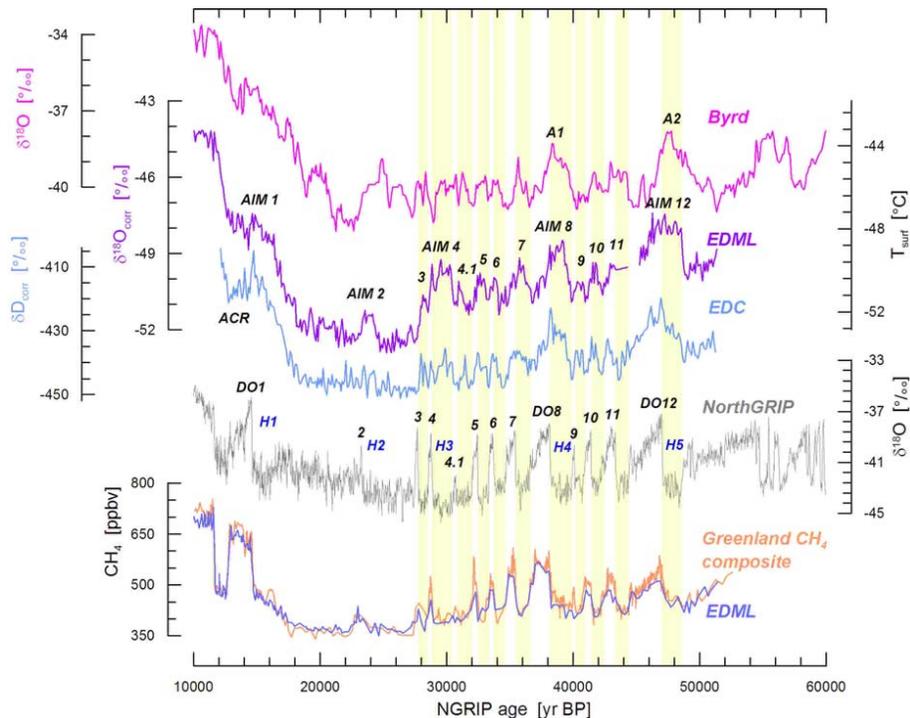
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**Fig. 10.** Methane synchronization of the EDML and the NGRIP records reveals a one-to-one assignment of each Antarctic warming with a corresponding stadial in Greenland (adapted from EPICA Community Members, 2006).

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