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Information available from ice cores has considerably increased over the last two years thanks to ice cores drilled at North GRIP in Greenland and at Dome C in Antarctica. We present these two successful international programs, in which French teams from Grenoble, Orsay and Saclay have been very active, and review the results currently available from these ice cores. The first one reaches the Eemian - the warmest part of the last interglacial around 120 ky BP (thousand years Before Present), which is the first time for a northern hemisphere ice core, whereas the second one extends the ice core record back to 800 ky BP.

EPICA drilling - Dome C.
Forage EPICA au Dome C.

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Paleoclimate from ice cores



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JEAN JOUZEL ET CLAUDE LORIUS ONT,
EN 2002, REÇU CONJOINTEMENT LA
MÉDAILLE D'OR DU CNRS.

One of the chapters of the Fourth assessment report to be published by the International Panel on Climate Change (IPCC Working Group I: the Science of Climate Change) in 2007 will deal with paleoclimate. This choice fully reflects the fact that past climates are providing a wealth of information relevant to the ongoing debate on future climate warming. Thanks to numerous results based on studies of tree-rings, ice cores and corals, combined with historical documentary sources, we now have a better knowledge of climate variability over the last centuries and millennia, which is important for detecting climate change. The climate of the Holocene, the warm period that since 11 ky (thousand years) has been highly favourable to the development of human societies, is significantly better documented than 10 years ago and it is the same for the succession of glacial and interglacial periods that have punctuated the Quaternary. At these longer timescales, we benefit from information extracted from various types of archives derived from the continent (lake sediments, speleothems, etc.), deep-sea sediments and deep ice cores drilled in Antarctica and Greenland, as well as from associated modelling. There is also an increasing amount of paleoclimatic information and modelling now available for longer geologic timescales, such as for the rapid global warming at the Paleocene - Eocene boundary, 55 million years ago.

“
 Past climates are providing a wealth of information relevant to the ongoing debate on future climate warming.”

Many aspects of past climate change are relevant to the future of our climate, including the existence of rapid changes first documented from ice cores and deep-sea cores and now also from numerous continental time-series. Polar ice cores have allowed us to track the increase in the concentration of the most important greenhouse gases since pre-industrial times and give indirect access to changes in other climate forcings. Comparison of climate changes and climate forcings at the glacial-interglacial timescale provides insight into the estimation of how climate reacts to forcings, showing that amplification processes have, as predicted by climate models, operated in the past. Records of past climates also contain information about climate mechanisms, such as those linked with changes in insolation, oceanic and atmospheric circulation and atmospheric composition. They also shed light on the complex interactions between climate and biogeochemical cycles.

It is beyond the scope of this article to review the results inferred from the different archives, each with their own limitations and drawbacks, but clearly providing useful complementary information. Rather, we will focus on polar ice cores that, as for most other oceanic or continental climate proxies, give access to local climate change data and to climate parameters of widespread geographical significance, and are unique in their capacity of tracking the composition of our past atmosphere through the analysis of entrapped air bubbles. By combining the data provided by both the ice and the air from the Antarctic and Greenland ice cores, key information directly relevant to the past and future evolution of our climate has indeed been acquired.

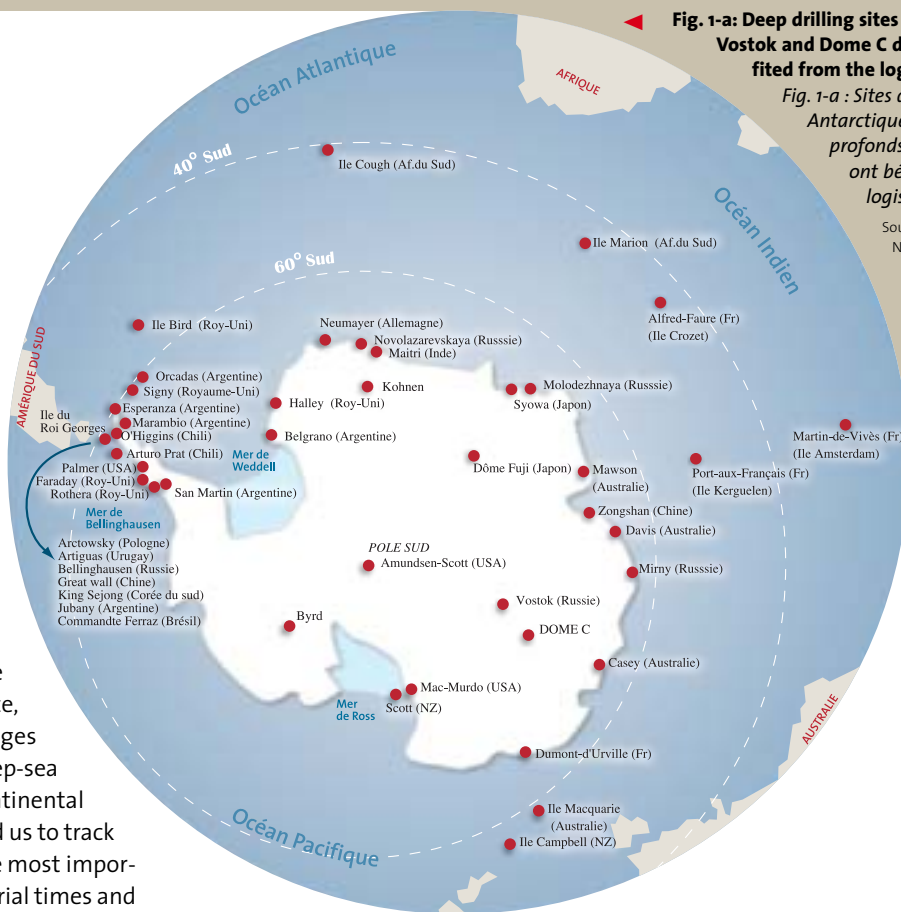


Fig. 1-a: Deep drilling sites in Antarctica. The deep Vostok and Dome C deep drilling have benefited from the logistic support of IPEV*.

Fig. 1-a : Sites de forages profonds en Antarctique. Les sites de forages profonds Vostok et Dôme C ont bénéficié du soutien logistique de l'IPEV*.

Source: adapted from North GRIP project members. *IPEV: Institut Polaire Français Paul-Émile Victor.

The climate in polar regions is reconstructed from water isotopes in ice from either deuterium or oxygen 18 concentrations, with the combination of the two providing information on the conditions prevailing in the oceanic moisture sources supplying polar precipitation. The temperature interpretation is straightforward over Antarctica where present-day observations can be used to calibrate the isotopic paleothermometer, whereas this method clearly underestimates temperature changes in Greenland by up to a factor of two for the Last Glacial Maximum, 20 ky ago. Most importantly, we note the discovery of a link between greenhouse gases and climate in the past, and the characterization of rapid climate changes. These results are based on the analysis of deep ice cores, such as the one drilled at the Vostok site (Fig. 1-a) that helps describe the evolution of Antarctic climate and atmospheric composition over the last 420 ky (Petit et al., 1999) and estimate global

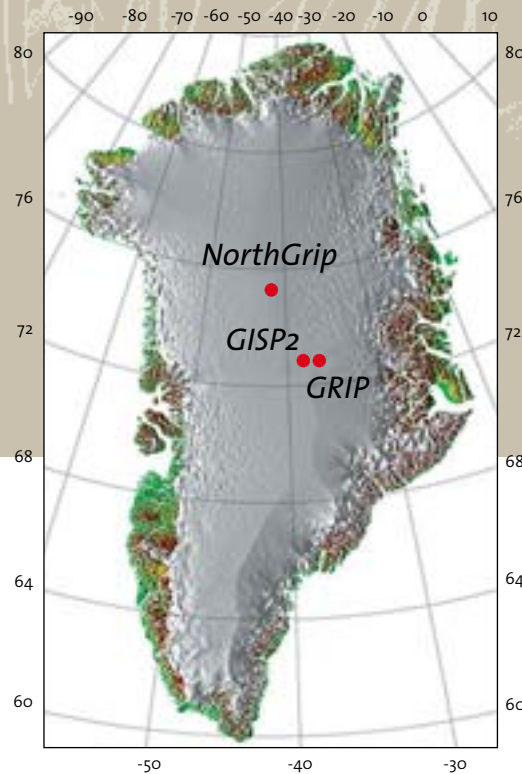
“
 Polar ice cores are unique in their capacity of tracking the composition of our past atmosphere through the analysis of entrapped air bubbles.”

“The North GRIP core extends uninterrupted back to 123,000 years ago.”

climate sensitivity (e.g. how our climate would react if the CO₂ atmospheric concentration were doubled), and such as GRIP and GISP2 (Greenland, Fig. 1_b) that precisely depict the rhythm of rapid changes during the last 100 ky. Other cores in high accumulation areas provide detailed access to more recent periods showing, in particular, the rapid increase in atmospheric concentrations of the main greenhouse gases influenced by anthropogenic activities (CO₂, CH₄ and N₂O). The recent drilling of two new deep (>3 km) ice cores at the sites of North GRIP in Greenland and Dome C in Antarctica has considerably increased the climatic information available.

The North GRIP deep ice core

The North GRIP drilling project (Fig. 1_b) was undertaken by an international consortium directed and organized by the ice core group of Copenhagen University. The first drilling was unsuccessful (drilling stacked in 1997 at a depth of 1,372 m), but the second drilling reached the bedrock at a depth of 3,085 m in 2003 and liquid water was indeed encountered at the base. This initially unexpected finding results from an atypical high geothermal heat flow with basal melting having the advantage of preventing flow disturbances as observed in the last 10% or so of the GRIP and GISP2 ice cores, with climatic records thus difficult to exploit for ages older than 100 ky BP. As a consequence, the North GRIP core (North Greenland Ice-core project, 2004 and Fig. 2) extends uninterrupted back to 123 ky BP (Fig. 3) within the last interglacial period (which was probably 5°C warmer than the Holocene). It thus allows an exceptionally detailed description of the last glacial inception with a Greenland record showing similarities with a deep-sea core on the Iberian margin. Comparison of the GRIP and North GRIP records over their common part (the last 105 ky) shows strong similarities as far as rapid changes are concerned, but also points towards regional climate differences between the two sites (Fig. 2). A temperature estimate methodology based on combined measurements of nitrogen and argon isotopes confirms that rapid warmings can reach up



◀ **Fig. 1_b: Deep drilling sites in Greenland.**
 Fig. 1_b : Sites de forages profonds au Groënland.
 Source: adapted from North GRIP project members

to 16°C, indicating that the conventional use of water isotopes underestimates temperature changes not only for the Last Glacial Maximum, but also for the so-called Dansgaard-Oeschger (DO) events, most likely due to changes in the seasonality of the precipitation under different climates.

The Dome C deep ice core

The Dome C Antarctic site (Fig. 1-a), where a first core was drilled in the seventies, is ideal for sampling very old ice because of an ice thickness of more than 3 km and a low accumulation. It was chosen 10 years ago as one of the drilling sites of the European project EPICA (European Project for Ice Coring in Antarctica) launched in 1995 by 10 European countries under the auspices of the European Science Foundation (ESF) with strong support of the European Communities. After a first drilling stacked at a depth of 780 m, a second drilling started in 2000 reached the bedrock (3,259.72 m) on December 29, 2004. The preliminary results published in 2004 (e.g. down to 3,139 m corresponding to an age of 730 ky BP) have since been extended down to the bottom of the core at a depth of 3,260 m. Figure 3 shows the deuterium profile, a proxy of local temperature change. Isotopic models confirm that the present-day isotope temperature relationship observed at the spatial scale on recent snow can be used, within ±20%, to interpret ice core deuterium profiles from East Antarctic cores in terms of local temperature change. Noticeably, the Last Glacial Maximum was about 10°C colder than the present day, whereas the corresponding temperature drop was more than two times greater in central Greenland.

GRIP and NorthGRIP isotopes vs. NorthGRIP depth

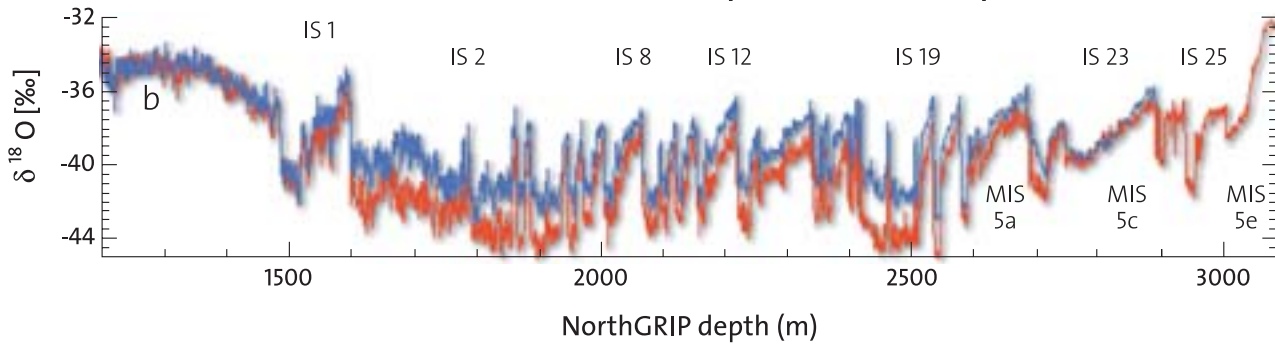


Fig. 2: Comparison of GRIP and North GRIP isotopic profiles over their common parts This figure shows the oxygen-18 content of the ice (expressed in ‰ / V-SMOW, Vienna Standard Mean Ocean Water), according to depth, going back to ~ - 100,000 years for GRIP (blue) and ~ - 120,000 years for North GRIP (red).

Fig. 2 : Comparaison des enregistrements isotopiques à GRIP et à North GRIP. Cette figure montre la teneur en oxygène 18 de la glace (exprimée en ‰ / V-SMOW, Vienna Standard Mean Ocean Water) en fonction de la profondeur jusqu'à ~ - 100 000 ans pour GRIP (courbe bleue) et jusqu'à ~ - 120 000 ans pour North GRIP (courbe rouge).

Source: adapted from North GRIP project members

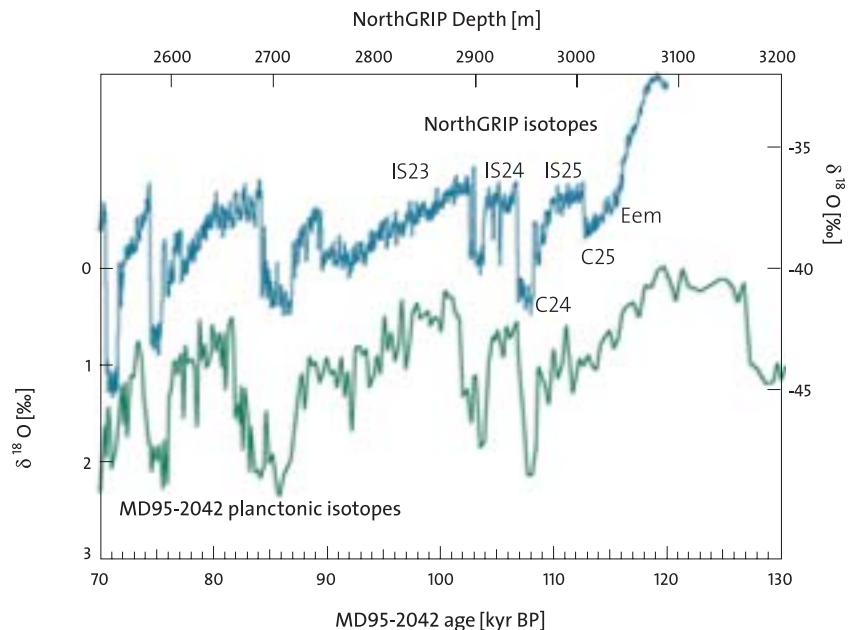
The time scale developed for the Dome C deep ice core, still preliminary, is based on an inverse dating method that combines an ice-flow model and an accumulation history (accumulation is deduced from the deuterium content of the ice, whereas thinning rate is computed with a one-dimensional flow model). The Dome C isotopic profile (EPICA Community Members, 2004) is in excellent agreement with those available from Vostok and Dome F over their common part (Fig. 4 and 5) confirming that the Antarctic surface temperature was warmer by up to 5°C during interstadials 5.5 (125 ky BP) and 9.3 (335 ky BP). For the first time, the excellent quality and the high resolution of the deuterium last glacial record shows, independently of its size, that each Dansgaard/Oeschger rapid event recorded in the Greenland ice has an Antarctic counterpart (Fig. 5).

The most striking feature of the EPICA record, previously observed in the deep-sea core record, is the clear change in the amplitude of glacial-interglacial changes before and after isotope cold stage 12 (~430 ky BP) with consistently colder and longer interglacials for the older period. Explaining this change of pacing remains a challenge for the paleoclimate community. The transition between stage 12 and the following interglacial (11.3), identified as an exceptionally long interglacial (28ky), has been studied in great detail. It shows resemblances with the transition into the present interglacial in terms of magnitude of changes in temperature and greenhouse gases, but with significant differences in the pattern of change. The similarities between the orbital parameters and our current glacial may imply that without human intervention, a climate similar to the present one would extend well into the future.

Fig. 3: The bottom part of the North GRIP isotopic record extending back to 123 ky BP (blue) compared to a deep-sea core record from the Iberian margin (green).
Fig. 3 : La partie profonde de l'enregistrement isotopique de North GRIP jusqu'à ~ - 120 000 ans (courbe bleue) comparée à un enregistrement isotopique océanique (courbe verte) de la marge ibérique.

Source: adapted from North GRIP project members

Iberian margin-NorthGRIP correlations





Extending the greenhouse gas record

As far as greenhouse gases are concerned, Raynaud *et al.* (2005) have recently extended the Vostok record back to 436 ky BP, a period corresponding to glacial stage 12. These data are in excellent agreement with those measured at EPICA Dome C for the same period (transition from stage 12 to 11). At this latter site, the last deglaciation had previously been studied in detail both for CO₂ and CH₄.

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The Concordia dome in Antarctica. Recovery of an EPICA drill core.

Dôme Concordia en Antarctique. Forage EPICA (European Project for Ice Coring in Antarctica) : extraction d'une carotte.

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The Concordia dome, Antarctica: EPICA drilling site.

Dôme Concordia, Antarctique : site de forage EPICA (European Project for Ice Coring in Antarctica).

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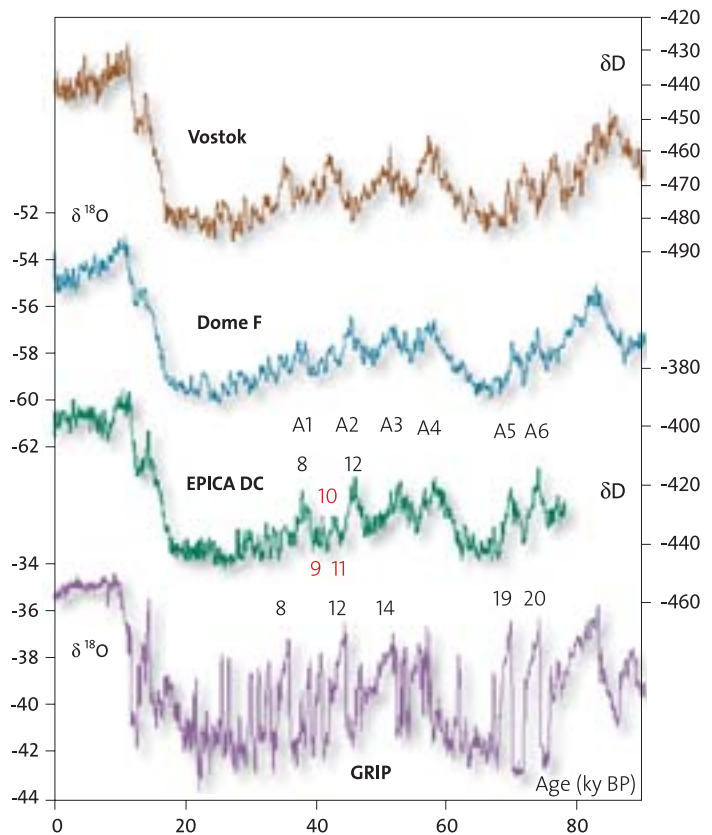


Fig. 4: Comparison of the GRIP isotopic record (Greenland) and records from East Antarctic sites (Dome C, Dome F and Vostok) over the last glacial period, each ice core being plotted on its own timescale. The major Antarctic events (A1, A2, etc.) are indicated, with the numbers corresponding to Dansgaard-Oeschger events and their Antarctic counterparts where possible.

Fig. 4 : Comparaison des enregistrements isotopiques à GRIP (Groenland) et en Antarctique de l'Est (Dome C, Dome F et Vostok) au cours de la dernière période glaciaire. Les résultats de chaque forage profond sont reportés sur leur propre échelle de temps (figure adaptée de Jouzel et al., en préparation). Nous avons indiqué les événements significatifs enregistrés en Antarctique (A1, A2...), ainsi que la numérotation des événements de Dansgaard-Oeschger et ceux qui leur correspondent en Antarctique, lorsqu'ils peuvent être aisément identifiés.

Source : adaptée de Jouzel et al., en préparation.

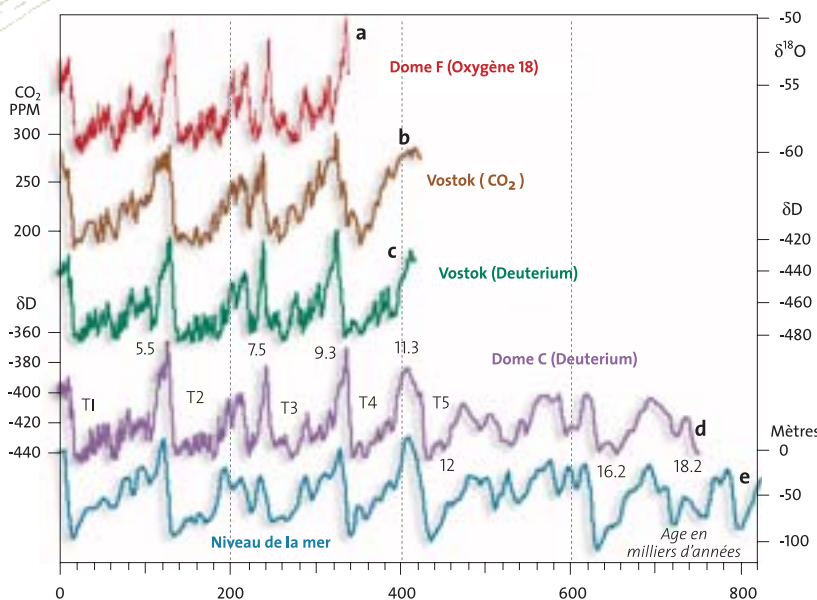


Fig. 5: Plot of records with respect to age:
a) the Dome F isotopic record,
b) the Vostok CO₂ record,
c) the Vostok isotopic record,
d) the EPICA Dome C isotopic record now extended back to 800 ky BP
e) the deep-sea core isotopic record.
 Fig. 5 : Cette figure montre, par rapport à l'âge (en milliers d'années) a) l'enregistrement isotopique au Dome F, b) l'enregistrement du CO₂ au site de Vostok, c) l'enregistrement isotopique de Vostok, d) l'enregistrement isotopique au site EPICA Dome C, étendu aux 800 000 derniers milliers d'années e) l'enregistrement isotopique marin sur cette même période.
 Source : adaptée de Jouzel *et al.*, en préparation.

As shown at Vostok from detailed studies on an earlier deglaciation, it appears that at the start of such transitions, the CO₂ increase lags Antarctic climate (by some 800 years). Similarities between changes in atmospheric CO₂ and Antarctic temperature suggest that changes around Antarctica play a role in the long term CO₂ change (whereas CH₄ changes are more under the influence of Northern Hemisphere processes). The situation thus differs from the recent anthropogenic CO₂ increase and we should distinguish between internal (such as the deglacial CO₂ increase) and external (such as the anthropogenic CO₂ increase) influences on the climate system. While the recent CO₂ increase has been clearly imposed first, as a result of anthropogenic activities, it naturally takes some time for CO₂ to outgas from the ocean once it starts to react to some climate change felt initially in the atmosphere. The sequence of events during deglaciations is fully consistent with CO₂ participating in the melting of the Northern Hemisphere ice sheet. The radiative forcing due to CO₂ may serve as an amplifier of initial orbital forcing, which is then further amplified by fast atmospheric feedbacks that are also at work for the present-day and future climate.

The EPICA Dome C core has now provided the opportunity of extending the record of CO₂ (Siegenthaler, 2005) and of CH₄ and N₂O (Spahni *et al.*, 2005) beyond the last four glacial-interglacial cycles, with the key question of how the greenhouse gases behaved before the clear change of pacing that the Antarctic climate underwent around 430 ky BP. The new data cover two additional climatic cycles back to 650 ky BP.

The significant co-variation of deuterium and CO₂ on millennial time scales persists also in this time period and the relationship between Antarctic temperature and CO₂ remains stable throughout the six glacial cycles despite this change of pacing. In general, CH₄ is also well correlated with Antarctic temperature, at least on a glacial-interglacial timescale (>40 ky), and one can confidently extend the result that present-day concentrations of CO₂, CH₄ and N₂O are unusual with respect to those encountered during the Late Quaternary to the last six glacial-interglacial cycles.

Future drilling activities

There is still much measurement and interpretation work to be done on these EPICA and North GRIP cores (with a second EPICA drilling which has reached the bedrock at Kohnen station in January 2006 and a new, more than 3 km deep, drilling successfully recovered at Dome F by a Japanese team), but the international ice core community is already looking towards the future with three major objectives: ⁽ⁱ⁾ extract ice older than one million years in East Antarctica with the hope of accessing the climate period dominated by a 40 ky periodicity, ⁽ⁱⁱ⁾ drill an ice core covering the entire Eemian and reaching back to the previous glaciation in North Greenland and ⁽ⁱⁱⁱ⁾ obtain a series of intermediate cores in coastal Antarctica. Projects aiming to fulfil the third objective are already in progress, whereas the Greenland project and a reconnaissance to identify potential sites to extract the oldest ice in Antarctica should be launched during the International Polar Year (2007-2009). ■



Carottes de glace et paléoclimat

Les glaces de l'Antarctique et du Groenland ont, depuis une vingtaine d'années, fourni des résultats importants vis-à-vis de l'évolution passée et future de notre climat, en premier lieu la mise en évidence d'une relation entre climat et gaz à effet de serre dans le passé et la découverte de variations climatiques rapides. Les deux dernières années ont permis d'accroître considérablement l'information disponible à partir de ces glaces polaires grâce aux forages de North GRIP au Groenland et de Dome C en Antarctique, permettant respectivement d'étendre les enregistrements au dernier interglaciaire (North GRIP) et aux huit derniers cycles climatiques (Dome C). Ces résultats indiquent que le dernier interglaciaire était, aussi bien au Groenland qu'en Antarctique, plus chaud que l'Holocène, d'environ 5°C. Ils mettent en évidence un lien étroit entre les variations rapides caractéristiques de la dernière période glaciaire au Groenland et les variations millénaires enregistrées en Antarctique. Dans cette région, le rythme des variations climatiques s'est modifié de façon notable il y a un peu plus de 400 000 ans et ce même changement de rythme est observé pour les concentrations en CO₂ dont la relation avec le climat Antarctique a été remarquablement stable depuis 650 000 ans. A aucun moment de cette période, les concentrations de CO₂, CH₄ et N₂O n'apparaissent avoir été aussi élevées qu'actuellement.