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C. R. Geoscience 337 (2005) 957–969
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External Geophysics, Climate and Environment

# Rapid deuterium-excess changes in Greenland ice cores: a link between the ocean and the atmosphere

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Accepted 23 May 2005

Available online 28 July 2005

Written on invitation of the Editorial Board

**Abstract**

Rapid climatic changes, the rhythm of which is fully described in Greenland deep ice cores, are also very well documented in the ocean (in particular in the North Atlantic) and on the continent. At these timescales, ice cores, deep sea-cores and continental records are still difficult to precisely synchronize. From the GRIP results, we show how a multiparametric ice core study allows us to circumvent this difficulty. The co-isotopic analysis of the deuterium and oxygen-18 concentrations in ice gives access to temperature both at the site (central Greenland) and in the evaporative moisture source region (North Atlantic). Rapid changes occur more or less rapidly from one event to the next, but are generally simultaneous. Surprisingly, our results suggest that the site and source temperatures vary in antiphase. This implies a drastic reorganization of the hydrological cycle in the North Atlantic at the time of rapid changes. ***To cite this article: J. Jouzel et al., C. R. Geoscience 337 (2005).***


**Résumé**

**Variations rapides de l'excès en deutérium dans les glaces du Groenland : un témoignage du couplage océan–atmosphère.** Les variations climatiques rapides dont les glaces du Groenland ont permis de décrire le rythme sont également très bien documentées dans l'océan (en particulier dans l'Atlantique nord) et sur le continent. À ces échelles de temps, les séries glaciaires, océaniques et continentales restent cependant difficiles à synchroniser de manière précise. À partir des résultats

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1631-0713/$ – see front matter 
doi:10.1016/j.crte.2005.05.011

obtenus sur le forage GRIP, nous illustrons comment l'étude multiparamétrique d'une carotte glaciaire permet de surmonter cette difficulté. L'analyse conjointe des teneurs en deutérium et en oxygène 18 de la glace donne accès aux température du site (centre du Groenland) et de la source océanique d'humidité (Atlantique nord). Les changements brusques observés surviennent plus ou moins rapidement d'un événement à l'autre, mais sont généralement simultanés. De façon surprenante, les résultats suggèrent que la température de la source océanique varie en antiphase avec celle enregistrée au centre du Groenland, ce qui témoigne d'une réorganisation drastique du cycle hydrologique dans l'Atlantique nord lors de ces événements rapides. ***Pour citer cet article : J. Jouzel et al., C. R. Geoscience 337 (2005).***


*Keywords:* Dansgaard–Oeschger events; GRIP ice core; Deuterium excess; Temperature; Site and oceanic source

*Mots-clés :* Événements de Dansgaard–Oeschger ; Carotte de GRIP ; Excès en deutérium ; Température ; Site et source océanique

## Version française abrégée

Même si l'existence de variations climatiques rapides est désormais bien documentée dans les glaces du Groenland [14,17,41], dans les sédiments marins, en particulier de l'Atlantique nord [2,6] et à partir de nombreuses séries continentales (par exemple, [16,52]), il reste difficile d'établir de façon précise la séquence des événements dans chacun des différents sites concernés et la rapidité avec laquelle ils surviennent. Dans cet article, nous présentons une méthode qui permet de lever cette difficulté, en s'appuyant sur des mesures obtenues sur un même carottage, ce qui évite les problèmes soulevés par la corrélation d'enregistrements d'origines différentes. Illustrée à partir d'une étude multiparamétrique de la carotte GRIP [14] forée au centre du Groenland (Fig. 1), elle s'appuie, en premier lieu, sur l'analyse conjointe des teneurs en deutérium et oxygène 18 de la glace.

Cette approche, dont la mise en oeuvre était jusqu'ici limitée aux grands forages de l'Antarctique [25,44–48] repose largement sur les résultats de modèles isotopiques [1,21,40] qui montrent que la teneur isotopique de la glace (deutérium, $\delta$D, ou oxygène 18, $\delta^{18}$O) reflète la température du site, tandis que l'excès en deutérium, $d = \delta\mathrm{D} - 8 \times \delta^{18}\mathrm{O}$, est avant tout influencé par les conditions (température, humidité, vent) qui règnent dans les régions océaniques d'où proviennent les précipitations (Fig. 2). Grâce à certaines hypothèses simplificatrices, mais suffisamment bien étayées, elle permet à la fois d'évaluer la température du site, $T_{\mathrm{site}}$ et celle de la source océanique, $T_{\mathrm{source}}$, et donc d'accéder à la séquence précise des événements dans les régions polaires et dans les régions océaniques « sources ». Néanmoins, une telle interprétation est plus délicate pour les enregistrements du Groenland que pour ceux de l'Antarctique [28,29,38,39]. Il faut alors tenir compte des variations saisonnières des précipitations entre, par exemple, climat glaciaire et climat actuel, alors que celles-ci peuvent, au premier ordre, être négligées pour l'Antarctique [30].

À partir d'une série continue et détaillée (tous les 55 cm) d'analyses conjointes ($\delta$D et $\delta^{18}$O) réalisées sur l'ensemble du forage GRIP [28,29], Masson-Delmotte et al. [39] ont développé une méthode qui, prenant en compte la saisonnalité des précipitations, permet d'exploiter cette approche dans le cas du Groenland. Afin d'illustrer la façon dont ces analyses isotopiques donnent accès à la séquence des événements, nous nous focalisons sur certaines périodes spécifiques (transitions rapides au cours de la dernière déglaciation, séries d'événements Dansgaard–Oeschger). Cet examen montre clairement que la situation varie d'un événement à l'autre. Ceci vaut, en particulier, pour la vitesse comparée des changements tels qu'ils sont ressentis au centre du Groenland, d'une part, et dans l'Atlantique nord, d'autre part (Fig. 3).

L'exploitation quantitative des résultats proposée par Masson-Delmotte et al. [39] rend bien compte des nombreuses observations qui, de façon concordante, indiquent qu'une interprétation conventionnelle du profil de teneur en oxygène 18 (basée sur les observations actuelles) sous-estime, dans certains cas d'un facteur deux, les variations de température au Groenland. Les variations de $T_{\mathrm{source}}$, très étroitement corrélées à celles de l'excès en deutérium, sont estimées à 6 °C entre période glaciaire et interglaciaire. Elles

sont caractérisées par une périodicité proche de 40 000 ans (tout au moins entre −20 000 et −80 000 ans), qui témoigne d'une modulation par l'obliquité [39]. L'explication pourrait être similaire à celle proposée pour l'Antarctique [47]. Elle met en avant le lien entre l'obliquité et la température et donc l'évaporation aux basses latitudes, d'une part, et le gradient d'insolation entre les basses et hautes latitudes, qui lui-même influe sur l'intensité du transport de vapeur d'eau, d'autre part.

Le résultat le plus surprenant concerne le comportement, lors des variations rapides, de la source océanique des précipitations du Groenland (avec l'Atlantique nord comme contributeur principal). En cas de réchauffement abrupt du Groenland (lors des événements de Dansgaard–Oeschger ou durant la dernière déglaciation), cette source se refroidit, alors qu'en un site donné de l'Atlantique nord, la température augmente. L'explication tient probablement au fait que cette source océanique se déplace de façon rapide et importante au moment des variations climatiques rapides, auxquelles sont donc associées des modifications drastiques du cycle hydrologique dans l'Atlantique nord. Cette idée est confortée par l'enregistrement de la teneur en calcium (indicateur des apports de poussière d'origine continentale), qui témoigne de variations tout aussi rapides, et généralement en phase, de la circulation atmosphérique.

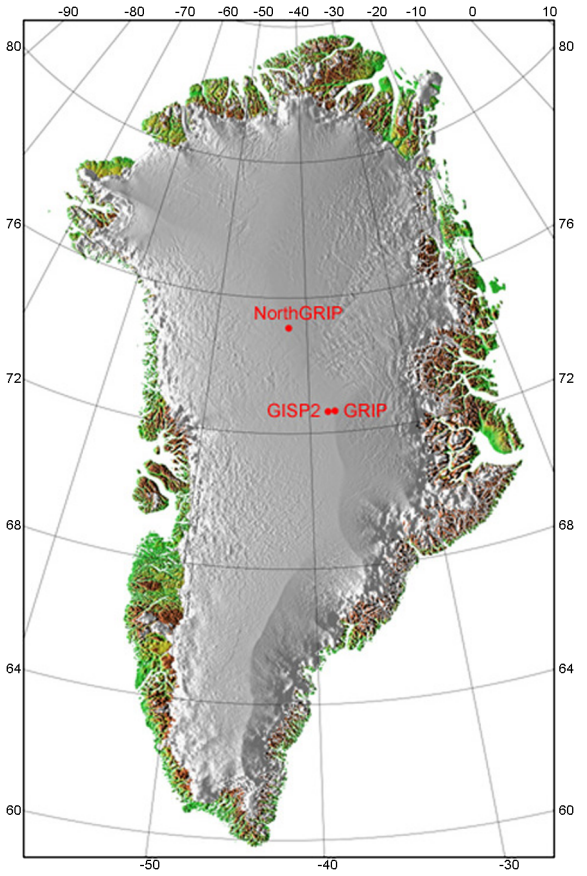



Fig. 1. Location of Greenland deep ice core drillings.

Fig. 1. Les sites de forages profonds au Groenland.

## 1. Introduction

The existence of rapid and large changes in the oxygen-18 concentration of Greenland ice cores (Fig. 1) first suggested by measurements performed on the Camp Century and Dye 3 records [11,12], has now been fully documented thanks to the detailed profiles measured along the GRIP [14], GISP2 [17] and North GRIP [41] cores. These rapid isotopic changes occurred under different climate conditions, e.g., at the onset and during the last glacial period (Dansgaard–Oeschger events, hereafter DO), during the last deglaciation (the transition leading to the Bölling–Allerod, BO transition, and the end of the Younger Dryas, YD), and in the Early Holocene (8.2-kyr event). Even if we face difficulties with temperature calibration [8,9,22,23], these isotopic changes correspond, without any doubt, to atmospheric temperature changes as independently demonstrated from measurements of nitrogen and argon isotopes in entrapped air bubbles [32,42,43]. Unlike water isotopes affected by seasonal changes in precipitation [30,53], highly accurate measurements of the isotopic composition of these two permanent gases allow precise estimates of temperature changes at the ice core site, showing warming events of up to 16 °C (DO 19 and DO 24) in probably a few decades [33–36].

As amply illustrated in this volume, these Greenland temperature changes have clear counterparts in the North Atlantic deep sea-cores records [2,6], as well as in numerous records from continental areas (e.g., [16,52]) and from the deep-sea records outside the North Atlantic. However, due to the lack of accurate absolute dating (both for Greenland and oceanic

records), the link between records from Greenland and from the North Atlantic (also interpreted as temperature changes with a strong link with the oceanic circulation prevailing in these regions) is still largely based on visual stratigraphy [2,6,49]. Additional information allowing us to tie the Greenland and North Atlantic records come either from common time markers and/or from the comparison of magnetic properties of oceanic sediments with cosmogenic isotopes fallout recorded in the Greenland ice [31,51]. As a result, the correspondence between oceanic and ice core rapid events can, in most cases, be established without any ambiguity. Still, it is difficult to directly assess their exact timing with a precision better than a few centuries. In addition, the rapidity of abrupt oceanic changes cannot be determined with a very high precision, due to the limited resolution of oceanic records, except in special settings such as for laminated sediments from the Cariaco Basin [20]. Ice cores offer a way to circumvent this difficulty. Combining deuterium (the deuterium, denoted D, is the hydrogen stable isotope of mass 2) and oxygen-18 measurements on the same ice sample opens the possibility to access to conditions prevailing in the oceanic regions providing moisture at the corresponding precipitation site. The existence of such a link was first demonstrated applying a simple Rayleigh-type isotopic model, which shows that the deuterium excess parameter (hereafter the excess), $d = \delta D - 8 \times \delta^{18}O$ ($\delta D$ and $\delta^{18}O$ are the water isotopic compositions expressed in $\delta$ units per mill versus V-SMOW, the Vienna Mean Ocean Water), defined by Dansgaard [10], depends mainly on the surface temperature and relative humidity in the moisture source regions [21,40]. From Antarctic ice cores excess records, this property has been extensively used to get information on the changes of the hydrological cycle in the Southern Hemisphere at different timescales [25,44–48]. In Greenland, until recent and ongoing studies based on excess profiles measured on GRIP and North GRIP ice cores [28,29,38,39], this approach was limited to two time spans of the Dye-3 core [13,21], the periods corresponding to the end of the Younger Dryas and to a sequence of three DO events, DO 5, 6 and 7 from around 30 kyr BP (thousands of years Before Present) and to the last millennium on the GRIP core [19].

In this article, we present and discuss recently available GRIP deuterium-excess data [28] focusing on rapid changes from the last glacial period and from the last climatic transition. Our purpose is twofold. First, we show how combining deuterium and oxygen-18 measurements allow to link rapid changes occurring in the North Atlantic and in central Greenland and to assess their timing. Second, based on a recent work conducted by Masson-Delmotte and co-authors [39], we describe how the use of both isotopes can lead to improved estimates of temperature changes in central Greenland and give information on concurrent conditions prevailing in the evaporative oceanic source regions.

## 2. Water isotopes and moisture-source conditions

The deuterium-excess parameter characterizes the isotopic composition of a precipitation in a $\delta D/\delta^{18}O$ diagram with present-day annual precipitation falling on the Meteoric Water Line, $\delta D = 8 \times \delta^{18}O + 10$ [7]. Modern excess has thus an average value of 10, but however vary both spatially and temporally with changes documented at all timescales. The basic reason is that fractionation processes at the origin of observed isotopic distribution of HDO and $H_2{}^{18}O$ in the water cycle depend on two physical properties: the water–vapour saturation pressure and the molecular diffusivity of water, which respectively give rise to the equilibrium and kinetic effect [40]. Once these two types of fractionation are included, both simple [11,21,24] and complex [18,26] models of the water isotope atmospheric cycle show that the large-scale $\delta D$ and $\delta^{18}O$ features are primarily driven by the equilibrium effect, which taken alone well explains the slope of 8, at least outside polar regions where the kinetic effect at snow formation should be taken into account to fit observations [24].

Instead, the relatively subtle differences with respect to the MWL are largely governed by the kinetic effect. More important, on the global scale, is the kinetic effect associated with water–vapour evaporation at the oceanic surface. As a result, sea-surface conditions [40] such as relative humidity, temperature and, to a lesser degree, wind speed are key parameters for determining the excess of atmospheric water vapour and precipitation. However, relative humidity

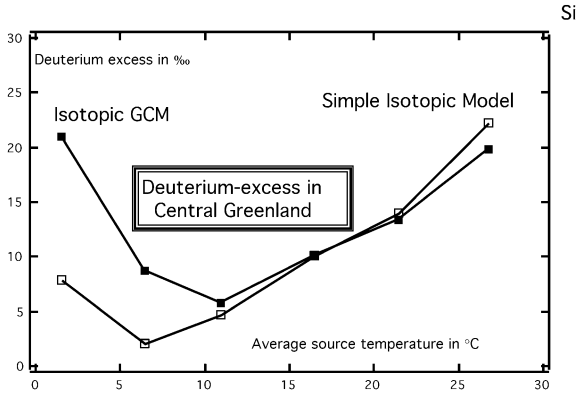



Fig. 2. Variation of the deuterium excess in central Greenland precipitation with respect to the temperature of the evaporative source, $T_{source}$, as simulated by the GISS GCM (thick solid line) and by the simple Rayleigh-type model (dashed line). This figure is adapted from Armengaud et al. [1].

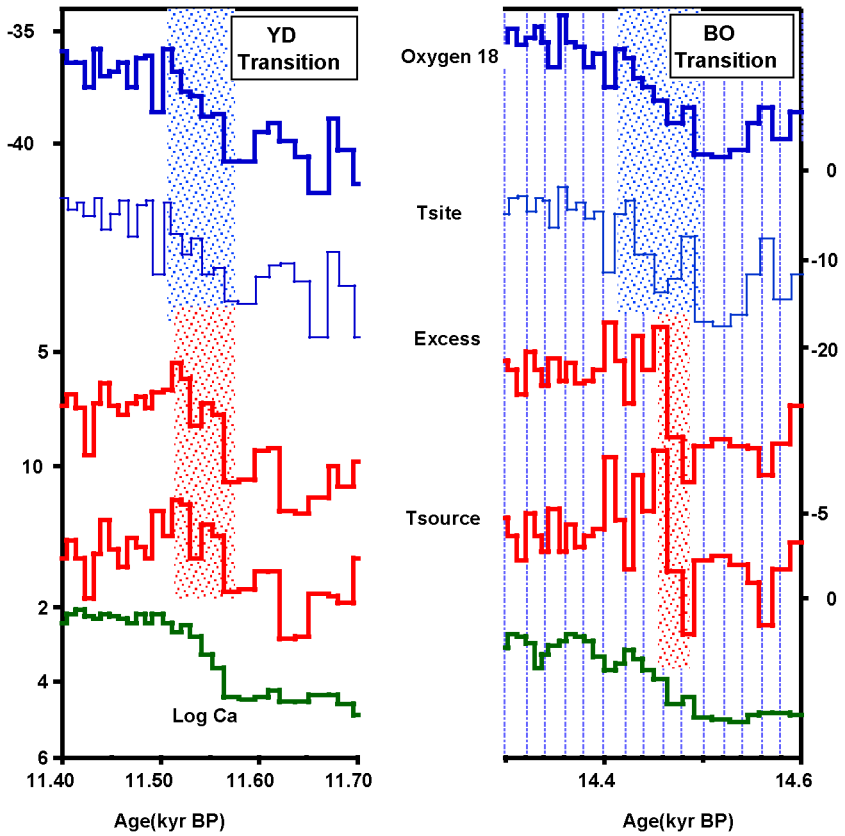
Fig. 2. Variation de l'excès en deutérium dans les précipitations du centre du Groenland en fonction de la température de la source océanique, $T_{source}$. Le deux courbes correspondent aux résultats obtenus par des simulations utilisant, soit le modèle de circulation générale du GISS (courbe continue, GCM), soit un modèle simple dit de Rayleigh. Cette figure est adaptée d'Armengaud et al. [1].

shows only small variations under different climatic conditions, at least once averaged over large oceanic regions, as shown from General Circulation Model (GCM) experiments. This implies that relative humidity at the oceanic surface has only little influence on the excess of polar snow, the same reasoning applying for wind speed. In turn, among these three parameters linked with the ocean/atmosphere interface, we are left with the temperature of the evaporative source (hereafter $T_{source}$) as the main driver of the excess recorded in worldwide precipitation included in polar snow, as illustrated in Fig. 2, adapted from an analysis of excess in Greenland snow performed by Armengaud et al. [1] using both simple (Rayleigh-type) and complex models (the GISS GCM implemented with water isotopes). This diagram well illustrates the excess/$T_{source}$ dependency, both simple and complex models showing a linear increase of the excess in central Greenland precipitation with respect to the $T_{source}$ (of about 0.8%/°C), at least for $T_{source}$ above 10 °C.

The fact that this relationship does not hold true for temperatures below 10 °C is attributed to the difficulty of accounting for the effect of seasonal sea ice (there is, in the GCM, coexistence of sea ice and of open ocean in these grid cells). Also, we should point out to the influence of parameters other than $T_{source}$. First, even keeping constant its excess, any change in the isotopic composition of oceanic surface waters modifies the excess of water vapour above the ocean [54] and of the precipitation worldwide [27]. Again, using simple and complex models [27], one can show that $\Delta d_{ice}$, the excess change resulting from the change in the isotopic content of oceanic waters is well approximated by $55 \times \Delta\delta^{18}O_{ocean} \times \delta^{18}O_{ice}$, where $\Delta\delta^{18}O_{ocean}$ is the change in the ocean $\delta^{18}O$ (e.g., a typical $\Delta\delta^{18}O_{ocean}$ glacial interglacial change of 1‰ results in a shift of about 2% in the excess of GRIP ice samples). Second, changes occurring at the precipitation site also affect the excess of falling snow, among them changes in the temperature of snow formation itself, closely related to $T_{site}$, the temperature at the surface, as well as possible changes in supersaturation conditions. In turn, neglecting second-order effects linked with relative humidity and wind speed, and assuming that the parameterisation adopted for the supersaturation at snow formation is valid under different climates (which is likely), deuterium-excess changes observed in polar snow can be expressed as a function of three variables, the isotopic composition of the oceanic water [50], which can be estimated from deep-sea core measurements, and the temperatures at the source, $T_{source}$, and at the site, $T_{site}$. As we will see below, the combined use of $\delta$D and $\delta^{18}O$ measurements allows independent estimates of $T_{site}$ and $T_{source}$.

## 3. The GRIP deuterium-excess record

GRIP is a more than 3-km-long ice core drilled in the frame of a European project: the Greenland Ice core Project. The bedrock was reached in 1992 in this central Greenland site and the continuous $\delta^{18}O$ ice record, measured at Copenhagen, was published the following year [14]. Deuterium measurements were then performed at LSCE Saclay on the same samples (every 55 cm) and the deuterium excess record available in 1995. At that time, we were however unsuccessful in providing a quantitative interpretation of this excess profile and this is why we have delayed its publication. In fact, a conventional approach aiming to estimate site and source temperature changes



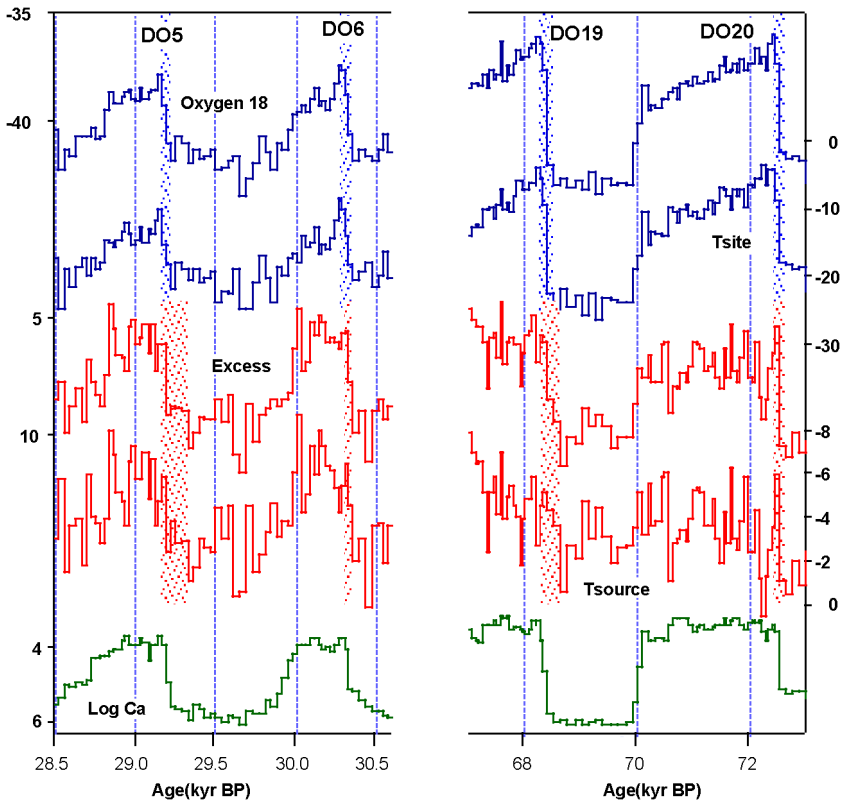

(**a**)

Fig. 3. (**a**) This figure shows, for the transition at the end of the Younger Dryas (on the left) and for the transition leading to the Bölling–Allerod (on the right), a series of five parameters w.r.t. time with; from the top to the bottom: the oxygen-18 content of the ice, the estimated temperature of the site, the excess, the estimated temperature of the oceanic source and the logarithm of the calcium concentration (the three bottom curves are reported using an inverted scale). We have indicated by a shading the period of change of these properties during rapid transitions. This figure is adapted from Masson-Delmotte et al. [39] using data measured on 55-cm samples.

Fig. 3. (**a**) Cette figure montre, pour les transitions rapides qui ont pris place à la fin du Younger Dryas (à gauche) et vers le Bölling–Allerod (à droite), une série de cinq paramètres en fonction de l'âge avec, de haut en bas : la teneur en oxygène 18 de la glace, la température du site, l'excès en deutérium de la glace, la température de la source et le logarithme de la concentration en calcium (les trois dernières courbes, $T_{\text{site}}$, Excess et ln Ca, étant reportées avec un axe inversé). Nous avons indiqué la durée sur laquelle se produisent des changements observés. Cette figure, adaptée de Masson-Delmotte et al. [39], utilise les données analysées sur des échantillons de 55 cm.

from $\delta$D and $\delta^{18}$O measurements led then to obvious inconsistencies. As fully discussed by Masson-Delmotte et al. [39], this difficulty has now been essentially overcome thanks to an approach accounting for changes in seasonality both for the accumulation of snow and its isotopic composition, and publication of the full GRIP excess record is now underway [29]. This record is shown in Fig. 4 (curve **b**), using a 100-yr time step back to 100 kyr BP (the GRIP core being affected by ice flow disturbances for older samples). The main results presented in these two articles are summarized in the next section.

In order to illustrate how GRIP co-isotopic data can, by themselves, give a clue on the timing between central Greenland and North Atlantic events, we first focus on data concerning specific time periods. We have selected the rapid warming events during the last climatic transition (Fig. 3a) and two sequences of Dansgaard–Oeschger events (Fig. 3b), DO 5 and 6, chosen because they include the time span over which




(**b**)

Fig. 3 (*continued*). (**b**) The same as in Fig. 3a for Dansgaard–Oeschger events 5 and 6 (left) and 19 and 20 (right).

Fig. 3 (*continué*). (**b**) Identique à la Fig. 3a pour les périodes correspondant aux événements Dansgaard–Oeschger 5 et 6 (à gauche) et 19 et 20 (à droite).

excess data are available on the Dye-3 core [13,21], and DO 19 and 20 (around 70 kyr BP). Here, we use original data, e.g., measurements performed on 55 cm sample, which corresponds to an average time resolution of ∼12 yr for the last deglaciation of ∼30 yr for DO 5 to 7, and of 80 yr for DO 19 and 20.

Each of the rapid warming events recorded by the oxygen-18 record (end of the YD, transition to BO, rapid warming events associated with DO events) is characterized by a rapid change in deuterium excess. As in Dye 3 [13], the end of the YD event is, at GRIP, marked by a rapid and large deuterium-excess decrease (∼5% change in both ice cores), interpreted by Dansgaard et al. [13] as reflecting a rapid retreat of the sea-ice cover). These authors noted that the change in excess (e.g., in oceanic conditions) was more rapid (20 years) than the temperature change in central Greenland (50 years). The GRIP results do not reflect however this differential behaviour, as it appears that GRIP oxygen-18 and excess changes are both completed in 50 years or so. Instead, such behaviour is observed for the BO transition (for which the results are not available at Dye 3). The excess decrease is quite rapid (20 years or less), whereas it takes about 100 years to see the associated warming completed in central Greenland.

The excess records of GRIP and Dye 3 are remarkably similar over the period covered by DO 5, 6 and 7. At both sites, the excess is in antiphase with the oxygen-18 record with a similar shift between cold and mild periods. Our time resolution is however too low to identify small phase shifts between the two records, as suggested for Dye 3 [21]. At last, we note that the excess change (presumably ocean driven) can be more or less rapid from one event to the next. This is further illustrated by DO 19 and 20 – both oxygen-

18 and excess changes are quite rapid for DO 20, whereas, for DO 19, this only applies for oxygen-18, the excess change being slower – and, indeed, such a variability in the oxygen-18 excess behaviour holds true over the entire GRIP record. Still, these various examples illustrate how useful can be ice core isotopic records to shed light on the strength of the link between atmospheric (as seen in central Greenland) and oceanic rapid changes.

We should keep cautious in our interpretation because the coefficient of 8 used to calculate the excess is somewhat arbitrary. Indeed, when calculated along the core (using 50 successive samples), the $\delta D/\delta^{18}O$ slope varies between 6.5 and 8.5, with glacial values close to 7.5 [29]. In turn, the excess might not be optimal to extract the additional information contained in the co-isotopic measurements, with respect to that derived from either $\delta D$ or $\delta^{18}O$. However, a principal-component analysis between the two isotopic series (not shown) indicates that the first component is highly correlated with either $\delta D$ or $\delta^{18}O$ (PC1, $r^2 = 0.99$), the second being quite similar to the excess. This parameter is thus an appropriate metrics to extract this additional information, at least over the series taken as a whole.

Still, one could suspect that part of the excess changes associated with rapid warming events is due to the particularly large local temperature change rather than to remote moisture-source effects. Would we adopt the slope of 7.5 observed during the glacial period instead of 8 that the above mentioned rapid changes would become less conspicuous. On the other hand, plotting $d$ versus $\delta^{18}O$ [29] allows to visualize the fact that for a given $\delta^{18}O$, e.g., presumably for a given local temperature, a large variety of excess values are encountered with well-defined patterns. This definitely confirms that the excess contains such additional 'source' information with respect either to $\delta D$ or $\delta^{18}O$. We explore in the next section how such information can be inferred using isotopic models.

## 4. Towards a quantitative interpretation of $\delta D$ and $\delta^{18}O$ GRIP profiles

Although isotopic GCMs are now extensively used to simulate water isotope distribution, there are only a limited number of experiments specifically dealing with the relationship between the excess of a precipitation and the conditions prevailing at its oceanic source. For example, the results shown in Fig. 2, which correspond to present-day conditions, have not been repeated for glacial conditions and more generally for different climates. Although very promising, the GCM approach is not yet helpful to interpret excess changes recorded in ice cores.

Instead, despite obvious limitations, Rayleigh-type models are perfectly adapted to this context, because a large part of the $\delta D$ and $\delta^{18}O$ variability can be explained by two variables only, $T_{site}$ and $T_{source}$. In addition, whereas $\delta D_{ice}$ and $\delta^{18}O_{ice}$ depend primarily on $T_{site}$ and to a lesser extent on $T_{source}$ [3], it is the reverse for $d_{ice}$. Moreover, the influence of a change in the isotopic composition of the ocean can be easily accounted for through a correction proportional to $\Delta\delta^{18}O_{ocean}$. In turn, one can easily extract $T_{site}$ and $T_{source}$ from co-isotopic $\delta D_{ice}$ and $\delta^{18}O_{ice}$ data, at least in a model world. For example, from a multiple linear regression analysis of the simple-model properties, Masson-Delmotte et al. [39] end up with the following estimates:

$$\Delta T_{site} = 1.32\,\Delta\delta^{18}O_{corr} + 1.04\,\Delta d_{corr}$$

$$\Delta T_{source} = 0.29\,\Delta\delta^{18}O_{corr} + 1.58\,\Delta d_{corr}$$

In these equations, the subscript $_{corr}$ means that the oceanic correction is taken into account and $\Delta$ refers to the difference with respect to modern conditions. This dual approach is now extensively used for interpreting measurements performed on Antarctic cores, where it provides quite consistent results. It has also been applied for the last millennium and the Holocene in Greenland, again quite satisfyingly, but the situation clearly deteriorates there if this inversion method is applied for the last glacial period and the following transition, providing quite unrealistic results (estimated $\Delta T_{site}$ are then much too low with respect to independent estimates obtained from argon and nitrogen isotopes). As fully discussed in [39], the situation is due to changes in precipitation seasonality. Such seasonality changes are probably moderate inside Antarctica between modern and glacial conditions [30] and in Greenland over the last millennium and the Holocene, so they can be neglected for the interpretation of isotopic profiles.

Instead, large topographic and atmospheric circulation changes during glacial (presence of the Laurentide ice sheet, larger extension of sea-ice, which makes

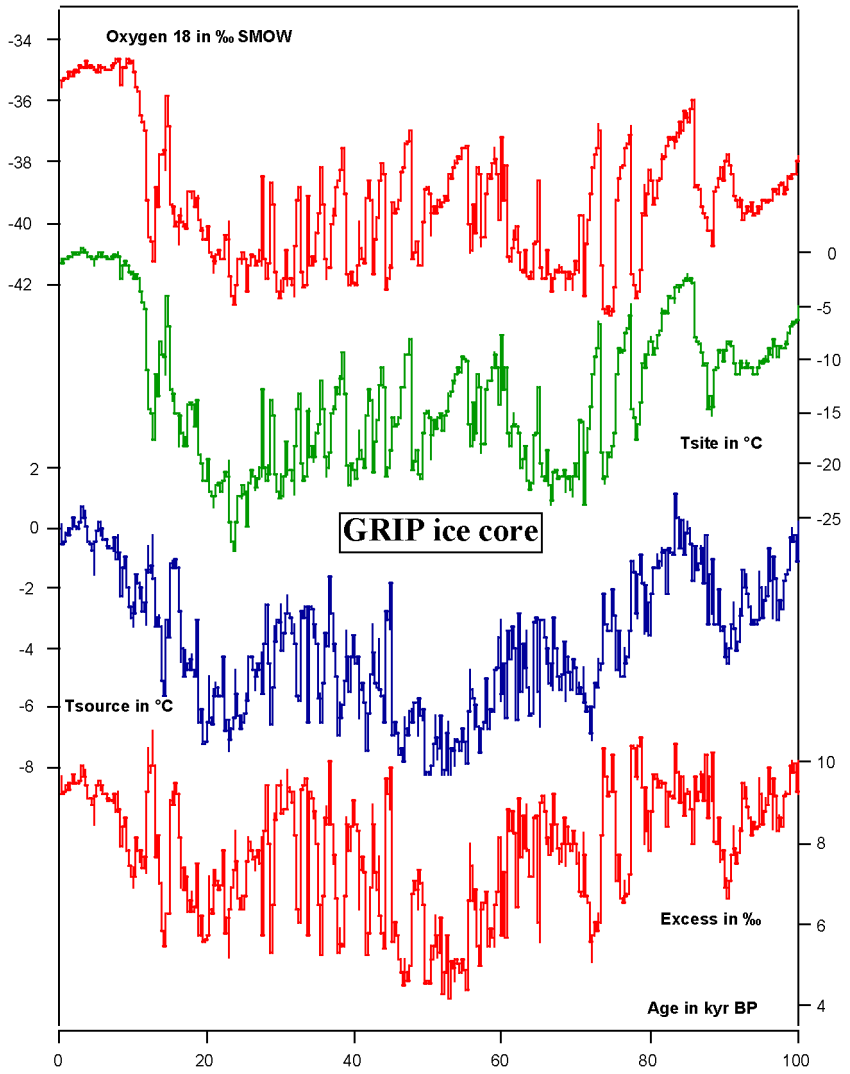



Fig. 4. Variation during the last 100 000 years (200-year time step) of the GRIP ice core oxygen-18 (top curve) and of its deuterium excess (bottom curve). Estimations of the changes in the temperature of the site ($T_{site}$) and of the source ($T_{source}$) are adapted from Masson-Delmotte et al. [39].

Fig. 4. Variations au cours des 100 000 dernières années (pas de 200 ans) de la teneur en oxygène 18 de la glace de GRIP (courbe du haut) et de l'excès en deutérium. Les courbes de la variation de la température du site ($T_{site}$) et de celle de la source océanique ($T_{source}$) sont adaptées de Masson-Delmotte et al. [39].

central Greenland a true continental site) are at the root of concurrent large seasonality changes, with a shift toward a much larger proportion of summer precipitation under glacial conditions. This seasonality shift convincingly explains why the conventional interpretation of water estimates temperature changes in central Greenland by up to a factor of 2 [8,9,22,35]. In their study, which accounts both for the seasonality of the precipitation fallout and of its $\delta$D and $\delta^{18}$O, Masson-Delmotte et al. [39] further illustrate this point. Using independent information from argon and isotopes (available for specific events), they then provide estimates of $\Delta T_{site}$ and $\Delta T_{source}$ over the last 100 kyr (Fig. 4).

The last glacial maximum (LGM) to Holocene warming is estimated to ~23 °C, twice higher than in-

ferred from a conventional approach using present-day observed gradients. This clearly shows the importance of accounting for seasonality. However, there is also a significant influence of the source temperature, which results in a systematic shift of the warm part of each D/O event towards colder temperatures. This is due to the antiphase between the $\delta^{18}O$ and excess rapid variations: when Greenland is warm, the moisture source is colder thus leading, if not corrected for, to too cold temperature estimates and vice versa. $\Delta T_{source}$ mimics the initial excess record, with a glacial–interglacial amplitude of $\sim 6\,^{\circ}C$. Rapid $T_{source}$ changes from 2 to $4\,^{\circ}C$ occur simultaneously, but in antiphase with rapid $T_{site}$ events, while these two climate variables appear in phase at longer orbital scales. As noted above, the large amplitude of rapid events in excess is partly due to large changes in Greenland's temperature itself and is less marked after isotopic inversion in $T_{source}$. Noticeably, there is, as for Antarctica, an imprint of obliquity fluctuations in the excess and records, however limited to the last period between 20 and 80 kyr BP. The mechanisms at work are probably the same as in Antarctica. In low latitudes, a low obliquity is associated with a high local mean annual insolation, which should result in higher sea-surface temperature, as recently suggested by a modelling experiment [37] and thus in a more intense evaporation. A low obliquity also implies a decrease in high-latitude insolation and temperature [5]. The resulting increased insolation gradient is associated with a more intense meridional temperature gradient and a more intense atmospheric transport. These two effects act together towards a dominant role of warm low-latitude sources when obliquity is low, thus explaining the observed link between deuterium excess and obliquity [39]. However, such a link is no longer observed between 20 and 10 kyr BP and before 80 kyr BP, possibly because these two periods, which correspond to large ice-sheet changes (deglaciation and glacial inception, respectively), are characterized by large-scale reorganisations of the northern hemisphere atmospheric circulation forced by ice-sheet growth or decay.

## 5. Conclusion

That $T_{source}$ and $T_{site}$ act in antiphase during rapid changes (also illustrated in Fig. 3 for specific events), a key result of our current interpretation of co-isotopic $\delta D$ and $\delta^{18}O$ GRIP profiles, was already noted by Dansgaard et al. [13] at Dye 3 for the rapid warming at the end of the YD. The concurrent cooling of the moisture source (our estimate from GRIP data is of $6\,^{\circ}C$) was explained by the fact that the retreat of sea ice, associated with this warming, opened up vast areas of cold surface seawater as moisture source contributor (with subsequent $T_{source}$ cooling). Still, this feature is very intriguing as much as it appears to systematically hold true, not only for rapid warming events during the deglaciation, but also for those associated with DO events. Whereas high-resolution North-Atlantic SST records exhibit rapid changes quite likely in phase with Greenland D/O events, the situation is somewhat reverse for $\Delta T_{source}$.

Obviously, we deal with different variables, $\Delta T_{source}$ representing a spatial average of local SST changes weighted by the respective contribution of each oceanic area to Greenland precipitation. Our proposed interpretation to explain this different behaviour between local and spatially averaged values of the same variable (SST) is that drastic changes in the polar front, the geographical location of Greenland main moisture sources, and thus of the atmospheric water cycle during glacial times [21] are associated with rapid events. When Greenland is cold, sea-ice cover is extensive and ocean temperatures much colder than nowadays at temperate latitudes, which thus cannot significantly contribute to Greenland precipitation. Evaporation is however maintained at lower subtropical and tropical locations providing precipitation in central Greenland largely in summer. Typically, a southward moisture source shift of 5° in latitude is compatible both with the LGM $\Delta T_{site}$ values and with local summer SST reconstructions. This is also consistent with temperature and salinity latitudinal profiles estimated from marine sediments, reflecting the shift of the dominant evaporative areas during rapid events.

Not surprisingly (given the linear relationships used in the inversion), the timing and morphology of $\Delta T_{site}$ and $\Delta T_{source}$ are quite similar to those described above for oxygen-18 and the excess (see Fig. 3). Obviously, we would like to have an independent confirmation for (example using appropriate coupled ocean-atmosphere simulations) of this unexpected somewhat opposite behaviour between local SSTs and $\Delta T_{source}$. We are aware of the limitations of the method we have

applied (use of a too simplistic Rayleigh-type isotopic model, which is not well adapted for cyclonic precipitation, oversimplification of the notion of oceanic source as part of the water providing moisture for central Greenland coming from continental regions and possibly from the Pacific Ocean [4], ...). Still, one cannot see how, for example a decrease of the excess (as recorded at the end of the YD) could correspond to an increase in $\Delta T_{\text{source}}$ (as we should expect from the well-documented SST increase at that time, if it were not a concurrent drastic reorganisation of the hydrological cycle in the North Atlantic), and we have thus strong arguments in favour of the correctness of our conclusion, at least qualitatively.

Such a large-scale hydrological cycle reorganisation is indirectly confirmed by the calcium composition of GRIP ice, a parameter reflecting first the strength of GRIP dust sources mainly provided by Chinese loess areas and second the efficiency of dust transport to Greenland [15]. The strong correlation between ln(Ca) and $\delta^{18}$O of ice was previously noted [15] and Masson-Delmotte et al. [39] have shown the similarity is even better with this reconstructed site/source temperature gradient. The meridional temperature gradient also shows a strong 40-kyr modulation paralleling obliquity fluctuations. These authors suggest that mean annual insolation, and thus obliquity that strongly controls the meridional atmospheric circulation, also indirectly control the strength of the dust source. A larger obliquity should correspond to a decreased annual mean tropical ocean temperature, an increased land–sea contrast in summer, and could enhance the summer monsoons, thereby decreasing the continental dust sources.

In conclusion, such an interpretation of the $\delta^{18}$O and excess GRIP data now provides a consistent picture of changes occurring over the last 100 kyr in Greenland and in the North Atlantic. First, accounting for seasonality allows reasonable local temperature estimates from the GRIP isotopic record. Second, large changes in geographical moisture-source location likely occurred both at the orbital and millennial scales. Third, the influence of obliquity on deuterium excess and moisture origin, already identified for Antarctica, is confirmed for Greenland: when cold conditions prevail in the mid and high latitudes, the moisture origin shifts to milder southwards locations [13,21]. Fourth, striking similarities between the calcium/dust record and the source/site temperature gradient, both strongly modulated by obliquity, could be linked with dust source areas through the land–sea temperature contrast. At last, we have illustrated how data from the GRIP ice core ($\delta$D and $\delta^{18}$O and Ca) can, for any given rapid event, provide a precise timing (decadal timescale, and possibly annual) of associated changes occurring on the continent, in the North Atlantic and in central Greenland.

## Acknowledgements

This work is a contribution to the Greenland Ice Core Project (GRIP) organized by the European Science Foundation. We thank the GRIP scientists, logistics support and core processors. We also thank the science foundations in Belgium, Denmark, France, Germany, Iceland, Italy, Switzerland, and in the United Kingdom, as well as the CEC programme.

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