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Rapid climate variability during warm and cold periods in polar regions and Europe

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Abstract

Typical rapid climate events punctuating the last glacial period in Greenland, Europe and Antarctica are compared to two rapid events occurring under warmer conditions: (i) Dansgaard–Oeschger event 25, the first abrupt warming occurring during last glacial inception; (ii) 8.2 ka BP event, the only rapid cooling recorded during the Holocene in Greenland ice cores and in Ammersee, Germany. The rate of warming during previous warmer interglacial periods is estimated from polar ice cores to 1.5 °C per millennium, without abrupt changes. Climate change expected for the 21st century should however be at least 10 times faster. **To cite this article:** V. Masson-Delmotte et al., *C. R. Geoscience 337 (2005)*.

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Résumé

Variabilité climatique rapide pendant les périodes chaudes et froides aux pôles et en Europe. Nous comparons les caractéristiques des événements climatiques rapides ponctuant la dernière période glaciaire aux pôles et en Europe à deux événements rapides se produisant pendant des périodes relativement chaudes : (i) l'événement de Dansgaard–Oeschger 25, premier réchauffement rapide de la dernière entrée en glaciation ; (ii) l'événement d'il y a 8200 ans, seul refroidissement rapide de l'Holocène au Groenland et en Europe. Les périodes interglaciaires plus chaudes montrent un rythme de réchauffement

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de 1,5 °C par millénaire aux pôles, sans variation abrupte. Le changement climatique attendu au cours de ce siècle devrait cependant être au moins dix fois plus rapide. **Pour citer cet article :** V. Masson-Delmotte et al., C. R. Geoscience 337 (2005). © 2005 Académie des sciences. Published by Elsevier SAS. All rights reserved.

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Au cours des vingt dernières années, l'occurrence d'événements climatiques rapides a été découverte dans le secteur nord-atlantique : les événements de Dansgaard–Oeschger (D/O) se produisent en quelques dizaines à quelques centaines d'années et sont liés à des instabilités des calottes glaciaires et de la circulation océanique [13,39]. De tels événements sont-ils susceptibles de se produire en réponse au réchauffement climatique anthropique, à la suite d'un arrêt de la circulation thermohaline [6] ? Y a-t-il des événements climatiques abrupts se produisant pendant les périodes chaudes, ou uniquement en période glaciaire ? Quelles sont leurs caractéristiques spécifiques ?

Cet article présente les méthodes développées au LSCE pour caractériser et comprendre les variations climatiques rapides dans le secteur nord-atlantique (en Europe et au Groenland) et en Antarctique (Tableau 1). Les quantifications des changements de température dans les glaces polaires sont obtenues à partir de l'analyse et la modélisation des isotopes stables de l'eau, qui peuvent toutefois avoir des biais systématiques au Groenland à cause de changements de l'origine ou la saisonnalité des précipitations [10,14,16]. Le fractionnement thermique et gravitationnel de certains gaz dans les névés polaires forment une autre méthode de quantification des changements abrupts de température au Groenland [16,17,20,21]. Les enregistrements de $\delta^{18}\text{O}$ et de CH_4 de l'air piégé dans les glaces polaires permettent de placer dans un cadre chronologique commun les variations de température reconstruites à partir des glaces des deux pôles [23–27], mettant en évidence une anti-phase entre les deux hémisphères. Pour évaluer la pertinence des reconstructions en région polaire vis-à-vis du climat de l'Europe, nous les comparons à la reconstruction du $\delta^{18}\text{O}$ des précipitations à partir des ostracodes benthiques du lac Ammersee, en Allemagne [52–54], et au changement de végétation dans le Sud de l'Europe, estimé par comp-

tage palynologique dans la carotte ODP 976 en mer d'Alboran [8].

Les D/O se présentent comme la succession d'une phase froide, relativement stable et durant quelques siècles, d'un réchauffement abrupt, suivis d'un retour plus progressif à des conditions froides. Une synthèse des données existantes montre des changements abrupts de température de 10 à 16 ± 3 °C lors des D/O au Groenland (Fig. 1), associés à de grandes fluctuations (50 %) du pourcentage de pollen de forêts tempérées du Sud de l'Europe. L'enregistrement d'Ammersee suggère des changements de température en Europe de 5,5 et $8,0 \pm 1,5$ °C lors du début du Bolling–Allerod et à la fin du Dryas récent. En Antarctique, la contre-partie des D/O atteint une intensité de 1 à 3 °C.

Le nouveau forage NorthGRIP au Groenland met en évidence le premier D/O (D/O 25) se produisant lors de la dernière entrée en glaciation. Cet événement a une amplitude réduite, pas de contre-partie australe, pas de bouleversement de la végétation dans le Sud de l'Europe, et se produit alors que le volume des calottes glaciaires est seulement à un tiers de leur niveau maximal (Fig. 2). Au contraire, les D/O suivants présentent déjà les mêmes caractéristiques qu'en pleine période glaciaire. Un changement de cycle hydrologique dans l'atmosphère a pu contribuer significativement à cette première instabilité.

Au cours de l'Holocène, un événement rapide est enregistré au Groenland et en Europe [23,36,37,43,53,54], marqué par un refroidissement de l'ordre de 4 ± 2 °C au Groenland ($2 \pm 0,5$ °C à Ammersee), pendant quelques décennies. Cet événement est également marqué dans le signal palynologique en Méditerranée, avec une diminution de 10 à 15 % de l'occurrence de forêts tempérées (Fig. 3). Une simulation numérique suggère que ce type d'événement a pu être provoqué par un apport brutal d'eau douce dans l'Atlantique nord, par suite de la dislocation de la calotte de glace de la baie d'Hudson et de l'écoulement brutal des eaux de fonte stockées dans le lac Agassiz [42].

Au cours de l'Éémien, environ 5 °C plus chaud que la période actuelle, il semble que la calotte groenlandaise ait perdu 50 % de son volume, essentiellement au sud, et que l'Antarctique de l'Ouest ait contribué pour moitié à l'augmentation de 4 à 6 m du niveau des mers. Lors de cette période plus chaude que l'Actuel aux pôles, le rythme maximal de réchauffement était de l'ordre de $1,5 \pm 0,3$ °C par millénaire aux deux pôles [39,56]. Les carottes de glace antarctiques ne montrent pas, lors cette transition, d'événements climatiques abrupts aussi larges qu'en période glaciaire. Cependant, le réchauffement anthropique attendu au XXI^e siècle devrait être au moins 10 fois plus rapide que ces variations passées.

1. Introduction

At glacial–interglacial timescales, the driving force of climate change is the modulation of the seasonal and latitudinal incoming solar radiation by changes in the orbital parameters of the Earth [2], amplified by climate feedbacks. In this context, glacial–interglacial climate change has a pacing of several thousands of years [40].

During the late 1980s and 1990s, a succession of rapid climatic changes, named 'Dansgaard–Oeschger events' (D/O), has been characterized along the last glacial period in the North-Atlantic sector, occurring at timescales faster than the orbital forcing, decades to centuries, and involving instabilities of glacial ice sheets and ocean circulation [13,39]. The discovery of the capacity of the climate system to generate such rapid climate changes raised the concern for possible future climate surprises and non-linear responses to the anthropogenic-induced warming, such as a collapse of the oceanic thermohaline circulation [20]. What is the palaeoclimatic evidence for abrupt climate change occurring during periods warmer than full glacial conditions?

We briefly discuss here the methods used in the 'Laboratoire des sciences du climat et de l'environnement' (Grenoble, France) to characterise and understand rapid climate changes from climate archives in the North-Atlantic sector (Europe and Greenland) and in Antarctica. We then focus on the signature of two rapid events occurring (*i*) at the onset of the last glacial inception (D/O 25), and (*ii*) at the beginning of the

current interglacial period (8200 yr ago), and discuss their possible causes. We also quantify the rate of temperature increase at polar locations during previous, warmer interglacial periods, which do not exhibit any Antarctic evidence for abrupt events as large as during the last glacial.

2. Overview of archives and methods to characterise rapid events

2.1. Ice cores

In this paper, we discuss the specific signature of rapid events both during warm and cold periods based on specific archives. Among these, the deep Greenland ice cores (Table 1) play a central role in documenting continuously the temperature evolution in high northern latitudes [14,18,39]. Low-resolution ('bag measurements') water-stable isotope measurements conducted on these deep ice cores offer temporal resolutions of typically 4 yr during the Holocene [23] and 50 yr during the last glacial period. Until a new precise dating of NorthGRIP can be derived from ongoing high-resolution continuous optical and chemical measurements, a preliminary common timescale of GRIP and NorthGRIP cores has been constructed [39]. The spatial distribution of $\delta^{18}\text{O}$ of polar precipitation is presently linearly related to local temperature, as a result of the progressive distillation of air masses and preferential loss of heavy molecules during their cooling from evaporative areas to the poles [12]. However, the use of this spatial relationship to quantify past Greenland temperatures from Greenland ice core $\delta^{18}\text{O}$ temporal fluctuations leads to a systematic underestimation of glacial–interglacial changes [11,24,25,45], most probably because of changes in the seasonal cycle of snowfall between cold and warm periods, as suggested by atmospheric general circulation models [57] and changes in moisture sources during rapid events [35]. New methods based on the gravitational and thermal fractionation of gases in the firn before close-off processes [17,30,45] have provided independent estimates of rapid temperature changes during 16 rapid events [21,31]. Fig. 1 displays the NorthGRIP $\delta^{18}\text{O}$ profile [39] together with the synthesis of gas fractionation available estimates of rapid temperature and atmospheric methane concentration changes. Reconstructed 10 to 16 °C rapid temperature increases

Table 1

List of sites, types of archives, and methods used to characterise rapid events as reviewed in this paper

Tableau 1

Liste des sites, des types d'archives et des méthodes utilisés pour caractériser les événements rapides rapportés dans cet article

Site	Latitude, longitude, elevation	Archive type	Timescale and temporal resolution	Proxy
Ammersee	48°00'N, 11°10'E	Lake sediments	15 000 yr 10 yr	Benthic ostracod $\delta^{18}\text{O}$
NorthGRIP	75.10°N, 42.32°W 2917 m a.s.l.	Ice core	123 000 yr Holocene 4 yr Glacial period	$\delta^{18}\text{O}$, deuterium excess, air isotopic composition
GRIP	72.35°N, 38.30°W 3200 m a.s.l.	Ice core	105 000 yr	$\delta^{18}\text{O}$, deuterium excess, air isotopic composition
Vostok	78°28'S, 106°48'E 3490 m a.s.l.	Ice core	420 000 yr Holocene 50 yr Glacial period 500 yr	$\delta^{18}\text{O}$, deuterium excess, air isotopic composition
Dome C	74°39'S, 124°10'E, 3240 m a.s.l.	Ice core	740 000 yr Holocene 20 yr Glacial period 50 to 100 yr	$\delta^{18}\text{O}$, deuterium excess
ODP site 976	36°12'N, 4°18'W 1108 m b.s.l.	Marine sediments	Holocene 25 to 200 yr glacial 50 to 500 yr stage 525 to 1000 yr	Pollen associations characteristic of warm and wet phases

are associated with strong methane variations (more than one half of the glacial interglacial amplitude) with simultaneous temperature and methane increases within 50 yr [16]. Methane fluctuations are expected to reflect changes in tropical and high-latitude wetland productivities.

The fluctuations of methane and air-oxygen isotopic composition ($\delta^{18}\text{O}_{\text{atm}}$) can be identified in ice cores from both poles. Owing to their residence time (10 yr for methane, 1000 yr of $\delta^{18}\text{O}_{\text{atm}}$), these global tracers have been used as a tool to construct common timescales for Greenland and Antarctic ice cores [1,3]. On such a common timescale, Greenland and Antarctic water-stable isotope profiles exhibit a see-saw behaviour [5,49], which was independently confirmed by a new method based on nitrogen or argon air isotopic measurements [7]: the southern temperature increases slowly 2000 yr before the sharp Greenland temperature increase; when the northern hemisphere heats up abruptly, the southern hemisphere temperature decreases.

In the case of Antarctica, the water-stable isotope composition of ice remains considered as a reliable quantitative temperature proxy [26]. We discuss here the level of glacial and interglacial variability recorded

in east Antarctic ice water stable isotopes from Vostok [40] and Dome C [15] (Table 1). The amplitude and rapidity of the Antarctic counterpart of Greenland rapid events remains limited (see next section) and therefore only one attempt to use the gas fractionation palaeothermometry method has been performed [6], showing a temperature change consistent within 20% with the classical interpretation of water stable isotope fluctuations. We will discuss here the Antarctic temperature stability for older periods not recorded in Greenland ice sheet, where higher accumulation rates induce a more rapid renewal time.

2.2. North-Atlantic and Europe

Rapid climate changes recorded in Greenland ice cores appear to occur in phase with reorganisations of the North-Atlantic deep water formation [4,50] and associated northward heat transport, together with changes in the northern hemisphere atmospheric circulation.

Simultaneous changes in European climate can be identified from high-resolution archives that can be placed on a common chronological frame. Among them, the reconstruction of precipitation $\delta^{18}\text{O}$ can also

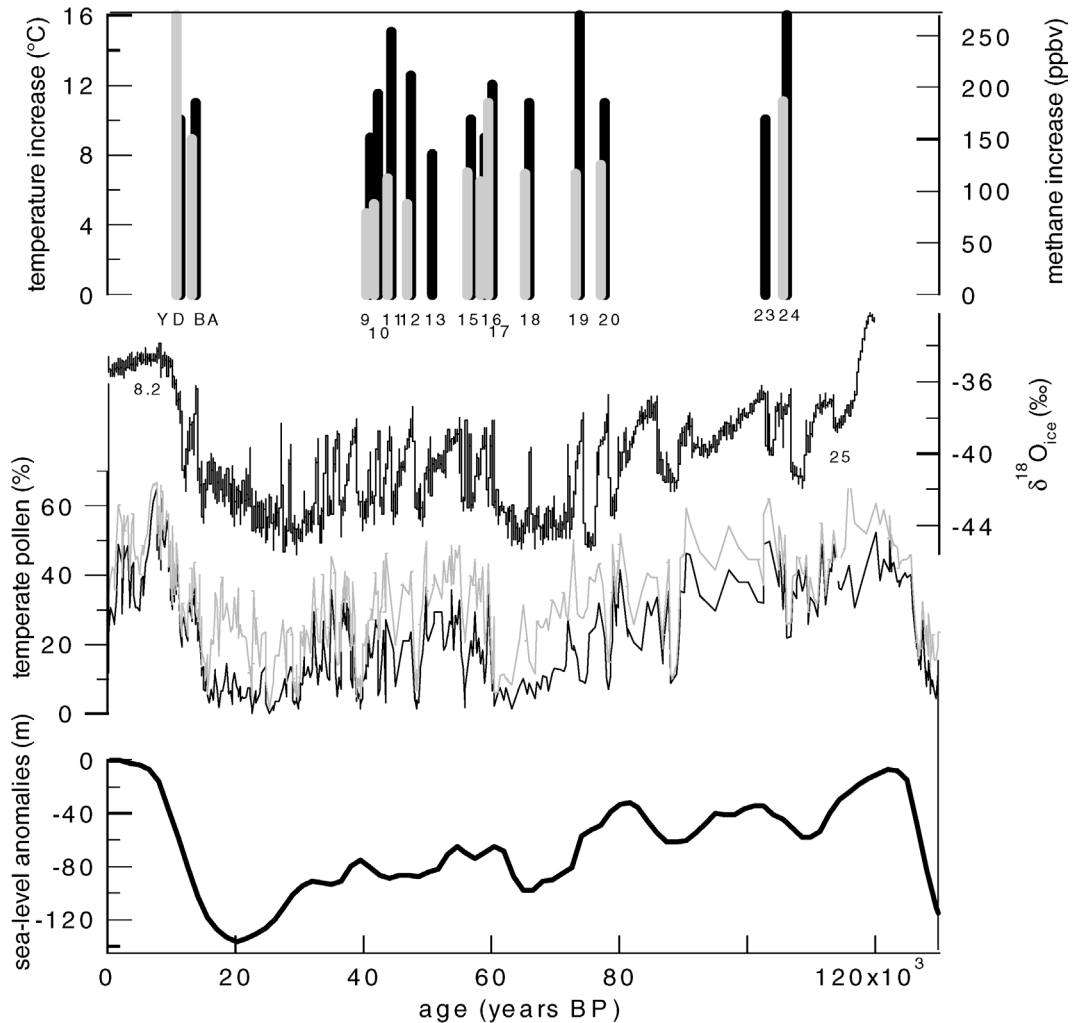


Fig. 1. Synthesis of rapid temperature changes recorded in central Greenland. Top panel, grey bars: amplitudes of methane changes; black bars: amplitude of temperature changes estimated from $\delta^{15}\text{N}$ and/or $\delta^{40}\text{Ar}$ in ice air (see references in the text). Mid panel, temporal changes in ice $\delta^{18}\text{O}$ re-sampled to a 40-yr time step from NorthGRIP ice core (black); percentage of temperate forest pollen (black) and temperate forest and ericaceae pollen (grey) in Alboran Sea. Bottom panel, marine sediment-based reconstruction of sea-level changes [55].

Fig. 1. Synthèse des changements rapides de température enregistrés au centre du Groenland. En haut, barres grises : amplitudes des changements de méthane ; barres noires : amplitude des changements de température estimés à partir du $\delta^{15}\text{N}$ et/ou du $\delta^{40}\text{Ar}$ de l'air piégé dans la glace (voir les références dans le texte principal). Au milieu, variations temporelles du $\delta^{18}\text{O}$ de la glace de NorthGRIP (pas de temps de 40 ans) (courbe noire) ; pourcentage de pollen de forêt tempérée (noir) et de pollen de forêt tempérée et d'ericaceae (courbe grise) dans la mer d'Alboran. En bas, estimation des variations de niveau des mers à partir de sédiments marins [55].

be achieved from lake sediments using lakes where (i) the deep-water temperature is near 4°C , (ii) the hydrological budget of the lake is controlled by the precipitation. In this case, the isotopic composition of benthic ostracod valves from similar species can be related to the isotopic composition of the deep-lake

water and further to the isotopic composition of the precipitation, with a decadal time resolution [52–54] and covering the last 15 000 yr. Such a reconstruction has been achieved from the sediments of Ammersee, southern Germany, on a common timescale with Greenland records (Table 1).

In southern Europe, high-resolution records of pollen preserved in marine sediments [8,44] also document past changes in vegetation cover associated with rapid events, on a common timescale with marine and ice records. Ocean Drilling Program (ODP) site 976 has been drilled in the Alboran Sea, the westernmost section of the Mediterranean Sea (Table 1) and downcore pollen assemblages identified [8]. It is assumed that the primary pollen contribution to the Alboran Sea sediments comes from west Mediterranean borderlands. The fossil pollen spectrum ranges from semi-desert to mountain deciduous and coniferous forests, and can be interpreted from the modern transfer functions developed for Eurasia and North Africa [41]. Here are only displayed the proportion of pollen representative of temperate forests taxa (Euro-siberian trees: *Quercus*, *Fagus*, *Carpinus*, *Corylus*, *Alnus*, *Betula*, *Tilia*, *Ulmus*..., associated with Ericaceae), as a proxy of warm and moist climates. The age model of [8] was refined and extended to 130 000 yr by correlation with deep sea core MD95-2042 [46] and NorthGRIP $\delta^{18}\text{O}$ record [39].

3. Characterisation of Dansgaard–Oeschger events and their signature in the North Atlantic including Greenland, Western Europe and Antarctica

The ice composition, air bubbles composition, dust content and chemical species of Greenland ice cores document the rapid climate variability during the last glacial period. These records give access to hemispheric scale reorganisations of the atmospheric hydrological cycle and transport. We discuss here the most local aspect, related to Greenland temperature reconstructions, either from water stable isotopes in the ice or from air-bubble isotopic composition.

As recorded in Greenland water stable isotope records [22,39], D/O events are associated with a cold, relatively stable phase ('stadial') lasting a few centuries to a few millennia, followed by rapid $\delta^{18}\text{O}$ increases (within about a century), with intensities varying from 3 to 5‰ in GRIP, from 4 to 7‰ in North-GRIP ice cores. This interstadial phase undergoes a gradual return to cold, depleted $\delta^{18}\text{O}$ levels. When converted to temperatures using the classical isotope–temperature relationship, these changes in ice isotopic

composition suggest temperature changes of typically 5 to 10 °C. However, alternative palaeothermometry methods have evidenced that water stable isotopes do not register faithfully past changes in Greenland surface temperature, due to reorganisations of the hydrological cycle. Changes in precipitation seasonality [25], in moisture source temperature [35] and possible changes in the vertical structure of the atmosphere (temperature profile, cyclonic activity...) make the classic reconstruction of glacial temperature with water isotopes through relationships based on present-day calibrations not accurate. New palaeothermometry methods based on $\delta^{40}\text{Ar}$ and $\delta^{15}\text{N}$ of air trapped in ice cores (see Section 1) indicate that (i) cold, stadial phases were less stable than indicated by ice $\delta^{18}\text{O}$; (ii) the amplitude of the stadial–interstadial transitions ranges from 10 to 16 °C. Such large amplitudes are not fully captured by intermediate complexity climate models used to simulate changes in the thermohaline circulation.

In Europe, precipitation $\delta^{18}\text{O}$ reconstructed from Ammersee extends back to 15 000 yr (onset of post-glacial lake). Although the signature of glacial rapid events cannot be identified, the Ammersee record clearly exhibits simultaneous abrupt warming at the onset of the Bolling Allerod and at the end of the Younger Dryas periods, suggesting local rapid temperature increases of respectively 8.0 ± 1.5 °C and 5.5 ± 1.5 °C, when estimates for rapid warming in Greenland suggest 11 and 10 ± 3 °C.

Temperate forest pollen data from the Alboran Sea show rapid fluctuations parallel to Greenland rapid events, with repetitive alterations of the temperate forest (mainly *Quercus*), then replaced by semi-desert vegetation, marking abrupt shifts between warm-moist (interstadial) and cold-dry (stadial) conditions [8]. The age scale does not enable us to estimate precisely the vegetation response time, occurring within a few decades to centuries. Changes in the percentage of the temperate pollen reveal amplitudes of rapid fluctuations as large as 50%, to be compared with a glacial–interglacial change of 70%.

The southern hemisphere counterpart of northern hemisphere rapid events can be identified in Antarctic ice cores [47,48]. Progressive (millennial scale) warming and cooling can be found, with amplitudes varying between 1 to 3 °C (corresponding to 10–15‰ in δD), and peaking about 2000 yr after the peak warmth in the

north [6]. Ongoing detailed measurements conducted on EPICA Dome C ice cores suggest that each D/O event could have an Antarctic counterpart (not shown).

4. Rapid climate variability during warm periods

The $\delta^{18}\text{O}$ record measured along the Greenland deep ice cores drilled at Summit in the 1990s suggested a generalised instability of climate with the persistence of rapid events during what was supposed to be the ice from the previous interglacial period [14]. However, detailed inspections of the ice stratigraphy, including analysis of the air trapped in the ice, demonstrated that these abrupt fluctuations of ice $\delta^{18}\text{O}$ resulted from a complex ice flow above bedrock and an unpreserved stratigraphy. A tentative reconstruction of the sequence of layers based on a correlation with methane and $\delta^{18}\text{O}_{\text{atm}}$ with the undisturbed reference from Vostok did not show any evidence for a true climatic rapid event during the previous interglacial period [28,29].

4.1. Onset of last glaciation: D/O 25

The recently drilled NorthGRIP ice core offers an undisturbed record of the last glacial inception and reveals a new rapid event, D/O 25, occurring about 115 000 yr ago when the northern hemisphere ice volume reaches about 1/3 of its glacial extent [39]. This first rapid warming shows a small $\delta^{18}\text{O}$ amplitude in NorthGRIP ice (about 1/3 of typical D/O events), and no Antarctic counterpart can be identified in Vostok available record (Fig. 2). In contrast, the next two rapid events (D/O 23 and 24) have the classical D/O characteristics, including the see-saw signature in Antarctic ice [9,32]. Mediterranean pollen data (Fig. 3) show that the interglacial forest environment is preserved during this period (mean percentage of temperate pollen around 40 to 50%) but rapid temperature pollen drops of increasing intensity (10 to 20%) occur during D/O events 25 to 23, reflecting that the early Greenland millennial scale variability has an European counterpart. The first D/O interstadial may be at least partly induced by changes in the atmospheric water cycle [27,51] and be associated with a latitudinal redistribution of heat transport in the northern hemisphere,

without drastic interhemispheric reorganisations as in the case of the next D/O events.

4.2. Holocene: 8.2 ka BP event

The only rapid event identified in Greenland during the Holocene [23,36] is a rapid cooling recorded in Greenland ice core, and also in Western Europe (so-called 8.2-ka-BP event) [37,53,54] and only few marine records in the Northeast Atlantic [43]. This cold event seems related to the decay of the Hudson Bay ice dome and the abrupt drainage of Lake Agassiz, as suggested by intermediate complexity climate models [42]. The Greenland record of the 8.2-ka-BP event, when smoothed with a 50-yr time step, shows a 200-yr-long $\delta^{18}\text{O}$ decrease with an amplitude of 1.6 to 2‰, corresponding to a temperature decrease reaching $4 \pm 2^\circ\text{C}$ during a few decades. Similar events punctuate most of the warm phase of D/O events. Although taking place during the Holocene interglacial period, this rapid event is the result of the final decay of non polar ice sheets. The detection of a simultaneous change in Ammersee Lake precipitation $\delta^{18}\text{O}$, showing a 1‰ decrease suggests a parallel cooling over Western Europe, with an annual mean temperature decrease of about $2.0^\circ \pm 0.5^\circ\text{C}$ and large-scale climate changes in the north Atlantic sector. Mediterranean pollen data also capture the 8.2-ka-BP event, marked by a 10 to 15% decrease in the percentage of temperate pollen, lasting about one millennium.

Although a common timescale has not been explicitly constructed for the Early Holocene, Antarctic ice cores undergo a cooling episode about 8000 yr ago, associated with the end of the Early Holocene optimum [33,34]. This time period indeed corresponds to the final decay of the Laurentide ice sheet, and large scale reorganisations in the atmospheric and oceanic circulations. Within the chronological uncertainties, it seems that there is no Antarctic counterpart of the 8.2-ka-BP northern hemisphere cooling, suggesting again that no large-scale interhemispheric heat transport redistribution is taking place.

4.3. Detection of abrupt changes during past warmer interglacial periods

Long palaeoclimatic records can also be used to assess whether rapid climate changes occurred during

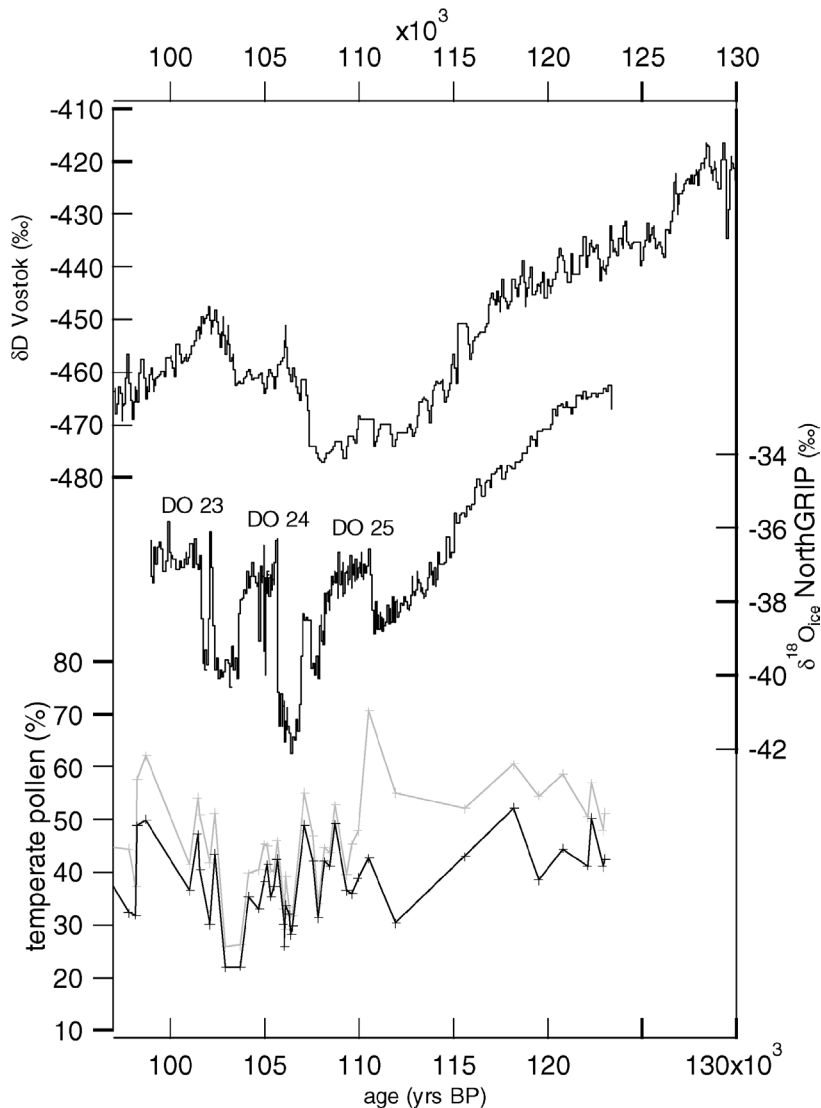


Fig. 2. Common timescale constructed for Vostok and NorthGRIP during the previous interglacial period based on air $\delta^{18}\text{O}$ measurements [32]. Comparison with the percentage of pollen in the Alboran Sea.

Fig. 2. Construction d'une échelle d'âge commune pour Vostok et NorthGRIP pendant l'avant-dernier interglaciaire, à partir de l'analyse du $\delta^{18}\text{O}$ de l'air [32]. Comparaison avec les pourcentages de pollens de la mer d'Alboran.

interglacial periods that are warmer than the current interglacial. In Antarctica, water-stable isotope records from Vostok, Dome F and Dome C suggest that the peak warmth during the previous interglacial period, about 125 000 yr ago, was about $5 \pm 1^\circ\text{C}$ warmer than during the Holocene [56], with a rate of Antarctic temperature increase above the Late Holocene level of $1.5 \pm 0.3^\circ\text{C}$ per thousand years and without any

evidence of significant abrupt event during this particularly warm episode. The same order of magnitude of polar temperature change is estimated from NorthGRIP ice core in Greenland [39].

Together with sensitivity experiments conducted with a Greenland ice sheet model [10], NorthGRIP data suggest that, during the previous interglacial period, the Greenland ice sheet was significantly reduced

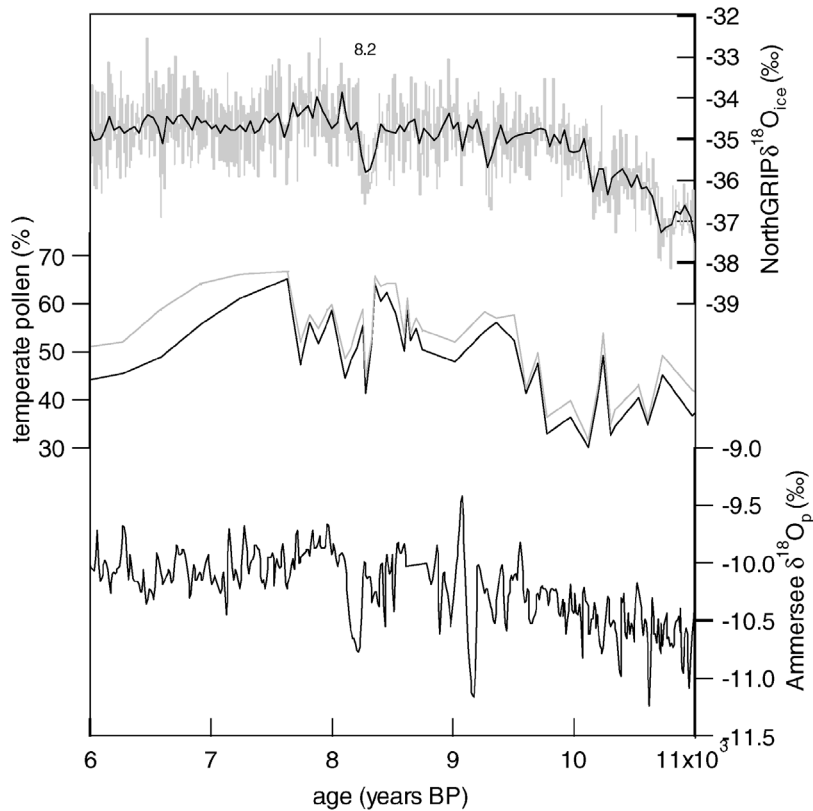


Fig. 3. Signature of the 8.2-ka-BP event in Greenland ice cores' $\delta^{18}\text{O}$ (NorthGRIP, top), Alboran Sea pollen (mid panel, grey, temperate forests and ericaceae, black, temperate forest), precipitation $\delta^{18}\text{O}$ reconstructed from benthic ostracods from Ammersee lake, south Germany (bottom).

Fig. 3. Signature de l'événement de 8,2 ka BP dans le $\delta^{18}\text{O}$ des glaces du Groenland (NorthGRIP, en haut) ; dans les pollens de la mer d'Alboran (figure du milieu : gris, forêts tempérées et ericaceae ; noir, pollens de forêt tempérée) ; dans le $\delta^{18}\text{O}$ des précipitations reconstitué à partir des ostracodes benthiques du lac Ammersee, dans le Sud de l'Allemagne (en bas).

in the South, but essentially similar to nowadays in the centre and the north. In response to this $\sim 5^\circ\text{C}$ warming, it is estimated that Greenland should have lost about 50% of its volume, essentially in the South, and would have contributed to a sea level rise of about 2 to 3 m, half of the total sea-level increase during marine isotopic stage 5e, estimated to be 4 to 6 m above present-day level [38]. These recent data suggest that west Antarctica and south Greenland ice sheets should have contributed almost equally to the global sea-level rise during marine isotopic stage 5e. Although associated with a significant decrease of parts of modern polar ice sheets, the available climatic records from Greenland (NorthGRIP), Antarctica (Vostok, Dome C, Dome F) and Europe [19] suggest a progressive warming above modern values without any interruption by a rapid event of significant amplitude or duration.

In a rather similar context, the transition from glacial conditions of stage 12 to the interglacial conditions of stage 11 takes place with a similar rate of temperature increase, and shows a small 'Antarctic Cold Reversal', occurring when ice isotopic levels reach modern values. This cold episode corresponds to a cooling of about $2.0 \pm 0.7^\circ\text{C}$ during a thousand years, rather comparable to the Antarctic Cold Reversal of the last deglaciation and termination III [47,48].

We have no evidence from polar ice cores that conditions warmer than now, encountered during previous interglacial periods, were associated with rapid climate change comparable to the glacial period rapid variability, linked to the instability of the Laurentide and Fennoscandian ice sheets and dramatic changes in the thermohaline circulation.

5. Conclusions and perspectives

The evidence from Greenland, Europe and Antarctica points out to a systematic occurrence of rapid events during glacial periods, in contrast with a few rapid events documented during warm periods.

By nature, the two events recorded in Greenland ice cores during warm periods are totally different. D/O 25 seems a small-scale precursor of further generalised glacial instability, possibly reflecting the shift of the ocean circulation to the glacial mode, particularly sensitive to the surface freshwater budget. This event takes place at a time period when the Earth's obliquity is a minimum. An intensified atmospheric hydrological cycle may have triggered the first instabilities of the ocean circulation, intimately linked with the progressive cooling at the glacial inception, however limited to the northern hemisphere latitudinal distribution of heat transport. Simulating this observed sequence of events during glacial inception, together with the large amplitude of Greenland rapid events during glacial conditions, will be the next challenge for transient climate models.

By contrast, the 8.2-ka-BP event is caused by an abrupt freshwater discharge from the remnants of glacial conditions. Within the temporal resolution of Antarctic Holocene records, this 8.2-ka-BP event does not seem to have an antiphase counterpart in the southern hemisphere, where this period corresponds to the end of the local Early Holocene optimum. Simulating the correct spatial and temporal signature of this 8.2-ka-BP event would be a specific benchmark to assess the realism of the thermohaline circulation of coupled climate models. For instance, it would be extremely fruitful to use climate models to test if the sensitivity of climate to a similar freshwater perturbation taking place during modern conditions and during Early Holocene conditions would be similar.

Future warming may induce an increased runoff and calving rate from the Greenland and west Antarctic ice sheets, with amplitudes of polar temperature changes expected to range between 2 and 5 °C at the end of this century [20]. Palaeoclimatic records point out to similar orders of magnitude for the polar temperature changes during the previous interglacial, about 125 000 yr ago, both in Antarctica and Greenland. Unfortunately, the published NorthGRIP record

does not cover the full transition from glacial to interglacial conditions. In Antarctica, all available ice core water-stable isotope data reveal temperatures about 5 °C above modern levels, and no abrupt event taking place during the rapid warming period above modern levels. Although the intensity of climate change during the previous interglacial period is rather similar to the intensity of warming expected for this century, the rate of temperature increase was more than 10 times slower (1.5 °C per millennium in the past, in response to the orbital forcing, to compare with 2 to 5 °C per century expected for the 21st century, in response to anthropogenic greenhouse gas accumulation in the atmosphere). Despite the evidence for a partial melt of probably both southern Greenland and West Antarctica, this past warm period did not undergo a dramatic reorganisation of the thermohaline circulation with an Antarctic counterpart. Testing the sensitivity of coupled climate/ice sheet models to the rate of temperature increase could provide a common framework in which to assess the realism of such simulations.

New deep-ice cores being currently drilled (Kohnen Station, in the southern Atlantic sector of Antarctica) or planned (NEEM, in the northwestern part of Greenland) should provide new high-resolution insights into the dynamics of rapid climate changes during the last climatic cycles.

Earth system models are being designed to explore the possibility of occurrence of rapid climate changes in the future, including the coupling between ice sheet and climate models. The realism of the physical representations in the models have to be assessed against the rapid events (or the absence of rapid events) documented during glacial and interglacial periods, including the data described here, before any confidence can be given to their prediction capabilities.

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