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## Modelling the oxygen-18 and rapid glacial climatic events: a data–model comparison

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### Abstract

Using a coupled climate model of intermediate complexity that explicitly simulates the oxygen-18 behaviour, we evaluate a recent scenario of abrupt climatic variability during the last glacial period against a sediment core record of the coast of Portugal (MD95-2042). In particular, we focus on a period centred on the Heinrich Event 4 (about 40 kyrs BP) and the surrounding Dansgaard–Oeschger events to explain some features of the sediment core record and question some choices of the suggested scenario. We demonstrate here (1) that the oxygen-18 signal recorded in the planktic foraminifera during D/O events is likely to be due almost entirely to temperature at the location of this core, and (2) that we cannot reproduce the observed oxygen-18 variations in calcite for Heinrich events if we consider that the melting of icebergs occurred elsewhere than in the IRD belt. **To cite this article: D.M. Roche, D. Paillard, C. R. Geoscience 337 (2005).**

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### Résumé

**Modélisation de l'oxygène 18 et événements climatiques rapides en période glaciaire : une comparaison modèle–données.** À l'aide d'un modèle dit de complexité intermédiaire, incluant explicitement l'isotope 18 de l'oxygène, nous comparons un scénario représentant la variabilité climatique lors de la dernière période glaciaire à un enregistrement isotopique provenant d'une carotte de sédiments marins prélevées sur la côte portugaise (MD95-2042). Nous nous intéressons particulièrement à la période aux alentours de l'évènement de Heinrich 4 (vers 40 mille ans avant le présent) et aux évènements de Dansgaard–Oeschger qui l'entourent. Cette analyse nous permet d'expliquer certains aspects de l'enregistrement isotopique et de discuter certains choix du scénario utilisé. Nous montrons en particulier que (1) le signal enregistré par les foraminifères planctoniques lors des évènements de Dansgaard–Oeschger est dû pratiquement uniquement à un effet de température à l'endroit de la carotte MD95-2042 et que (2) nous ne pouvons reproduire les variations observées en oxygène 18 dans la calcite pendant les évènements de Heinrich, si l'on suppose que la fonte des icebergs a lieu ailleurs que dans la zone à détritiques. **Pour citer cet article : D.M. Roche, D. Paillard, C. R. Geoscience 337 (2005).**

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## Version française abrégée

Le climat de la Terre lors de la dernière période glaciaire (de 115 à 21 000 ans avant le présent) présente des oscillations brutales, de grande amplitude et affectant la plupart des régions à des degrés divers. Durant la période qui nous intéresse ici, on distingue deux types d'événements : les événements de Dansgaard–Oeschger (D/O), qui présentent des oscillations abruptes en température [1,5] de façon assez régulière [14], faisant probablement intervenir des changements dans la circulation thermohaline, mais dont la cause est encore largement inconnue aujourd'hui : les événements de Heinrich, caractérisés par la présence de détritiques d'origine glaciaire dans les sédiments de l'Atlantique nord [16], apportés par des icebergs provenant des calottes de glace laurentienne et fénno-scandinave. La fonte de ces icebergs tend, par l'apport d'eau douce à l'océan, à arrêter la circulation méridienne atlantique, refroidissant le climat autour de l'Atlantique nord [8,11,13,17]. Cette succession d'événements est enregistrée dans certaines carottes de sédiments, dont la MD95-2042 [19], à laquelle nous comparons nos simulations. Pour simuler ces événements climatiques abrupts, nous utilisons ici un modèle climatique dit de complexité intermédiaire appelé CLIMBER-2 [12,15], auquel nous appliquons le scénario de flux d'eau douce suggéré par Ganopolski et Rahmstorf [4]. Leur approche permet de reproduire correctement les variations de température observées au Groenland, mais n'apporte pas d'explication quant à la cause des événements de D/O. Nous reprenons ici cette approche mais, pour comparer nos résultats avec l'enregistrement isotopique de la carotte MD95-2042, nous avons besoin de définir un contenu isotopique aux flux d'eau additionnels. Cependant, le mécanisme donnant lieu aux événements de D/O n'étant pas connu, nous ne donnerons pas de contenu spécifique aux flux d'eau additionnels associés à ces événements. En revanche, pour les événements de Heinrich, le contenu isotopique est choisi de façon cohérente avec le contenu que peuvent avoir les icebergs, c'est-à-dire avec le contenu isotopique de

la glace provenant de calottes de basse altitude. Nous utilisons ici un contenu de  $-30\%$  (cf. [7]). La Fig. 1 présente les résultats du modèle à  $40^\circ\text{N}$  dans l'Atlantique. Les courbes (b) et (e) montrent l'isotope 18 de l'oxygène simulé pour la calcite, pour la surface et à 3000 m de profondeur, calculé d'après [10,18], comme suit :

$$\delta^{18}\text{O}_c = 21,9 + \delta^{18}\text{O}_w - \sqrt{310,61 + 10T}$$

où  $T$  est la température,  $\delta^{18}\text{O}_w$  le contenu en  $^{18}\text{O}$  de l'eau et  $\delta^{18}\text{O}_c$  le contenu en  $^{18}\text{O}$  de la calcite. La Fig. 1 montre que l'origine du signal simulé à la surface en terme de  $^{18}\text{O}$  de la calcite est différente, selon que l'on se trouve en période de type D/O ou en période de type « Heinrich ». Lors des événements de D/O, le signal est dû principalement à des changements de température (environ  $2^\circ\text{C}$ ). Lors de l'événement de Heinrich, le signal en terme de  $^{18}\text{O}$  de la calcite est un composite de variations partiellement antagonistes en température et en  $^{18}\text{O}$  de l'eau. En particulier, vers la fin de l'événement de Heinrich, un refroidissement de  $6^\circ\text{C}$  en surface est contrebalancé en partie par le signal de fonte dû aux icebergs. En profondeur, le signal en terme de  $^{18}\text{O}$  de la calcite est dû à des variations comparables en terme de  $^{18}\text{O}$  de l'eau et en température, dont les effets s'additionnent. La comparaison entre notre simulation et la carotte MD95-2042 [19] est reportée sur la Fig. 2. En première analyse, on peut voir que l'accord entre modèle et données en terme d'amplitude de variations est de bonne qualité. En revanche, nous ne parvenons pas à reproduire la valeur absolue pour les benthiques, à 3000 m de fond. Cela peut s'expliquer par la sous-estimation du refroidissement glaciaire de l'océan de fond que produit le modèle CLIMBER. Ce biais a déjà été noté précédemment [15]. Une caractéristique intéressante de notre simulation au regard des données est le maximum relatif durant l'événement de Heinrich, bien qu'il soit plus faible dans la simulation que dans les données. Ce maximum est dû à l'advection du signal de fonte au site considéré. Pour mieux reproduire l'amplitude de ce maximum secondaire, des expériences variant la magnitude du signal « Heinrich » ont été réalisées (elles ne sont pas incluses

ici), mais ne permettent pas d'améliorer le résultat significativement. Pour obtenir un résultat plus satisfaisant, il faut déplacer les flux d'eau additionnels vers la zone définie par les détritiques glaciaires (45 à 55°N) au lieu de la zone de formation des eaux profondes, comme suggéré par [4]. Cette première étude alliant simulation transitoire durant la période glaciaire et comparaison directe aux données via la simulation de l'isotope 18 de l'oxygène montre l'intérêt du procédé, tant pour l'amélioration des scénarii climatiques que pour la meilleure compréhension des enregistrements sédimentaires. Cette étude ouvre la voie à un champ d'application plus large, avec notamment une comparaison étendue à un ensemble d'enregistrements sédimentaires.

## 1. Introduction

The climate of the last glacial period (115 to 21 kyrs BP) is characterized by abrupt and large scale changes. These events are mainly of two types: the Dansgaard–Oeschger events – or D/O events, faithfully recorded in the Greenland ice-cores [1,5], and the Heinrich Events – or HEs [6]. The former are characterized by large abrupt warming and cooling, occurring with a fairly regular pacing of about 1500 years [14]. The mechanism driving the D/O events probably involves changes in the thermohaline circulation, though the ultimate causes are however not known. The stable periodicity might suggest a solar-induced mechanism, but internal oscillations of the climate system cannot be ruled out. On the contrary, the mechanism leading to Heinrich Events is much better understood. The presence in sediment cores of the North Atlantic of layers with high Ice Rafted Debris (IRD) content (discovered by [16]) have been explained by the melting of numerous icebergs in this region, which additionally provided a huge freshwater input to the North Atlantic. Modelling studies have shown that such an input would cause the thermohaline circulation (THC) to collapse, cooling the surface of the North Atlantic [8,11,13,17]. The succession of D/O events – that is of abrupt cooling and warming – cannot only be seen in Greenland ice-core records, but also in a few sediment cores where the  $^{18}\text{O}/^{16}\text{O}$  ratio measured in the calcite of planktic foraminifera shells is showing the same type of oscillations. In the core of Shackleton et

al. [19], the benthic signal looks similar to Antarctic ice core records and might be caused by temperature changes or by a water signal with low oxygen-18 content. The interpretation given by the authors of the original paper will be here re-assessed, together with a thorough analysis of the planktic signal.

## 2. Modelling approach

Recently, Ganopolski and Rahmstorf [4] have suggested a mechanism to reproduce temperature oscillations such as D/O events. It involved the input of a freshwater – or salt – flux to the North Atlantic to trigger changes in modes of the thermohaline circulation in a coupled climate model. Depending on its strength, the input of freshwater slows (as part of the D/O oscillation) or shuts down (Heinrich Event) the THC, inducing cooling periods for the North-Atlantic temperature. The input of a salt flux accelerates the THC, therefore warms the North Atlantic and consequently the temperature over Greenland. This mechanistic approach yields temperature variations consistent with those recorded in Greenland and Antarctic ice cores, but does not provide any explanation of the cause of the D/O events. The water forcing for the D/O events is here relatively small and could be related to some fairly regional changes in the precipitation–evaporation balance, sea-ice cover changes, etc.

Here, we aim at evaluating this scenario against the data and at showing the efficiency of an approach based on modelling an isotopic proxy in a climate model to better understand the sediment core record and to suggest improvements to the model. Therefore, we are using the same model of intermediate complexity, called CLIMBER-2 [12], in a version [15] including the  $^{18}\text{O}$  isotope to compare directly the model output and the isotopic data. The freshwater input scenario used here is shown in the first panel of Fig. 1. As in [4], the freshwater input is set in the Atlantic Basin, centred at 60°N. This is where the thermohaline circulation is most sensitive to changes in surface salinity, hence to the applied freshwater – or salt – signal. As we are also modelling the oxygen-18 isotope, we need an additional parameter in this scenario, namely the oxygen-18 content of the freshwater input. As we do not know the process that leads to the D/O

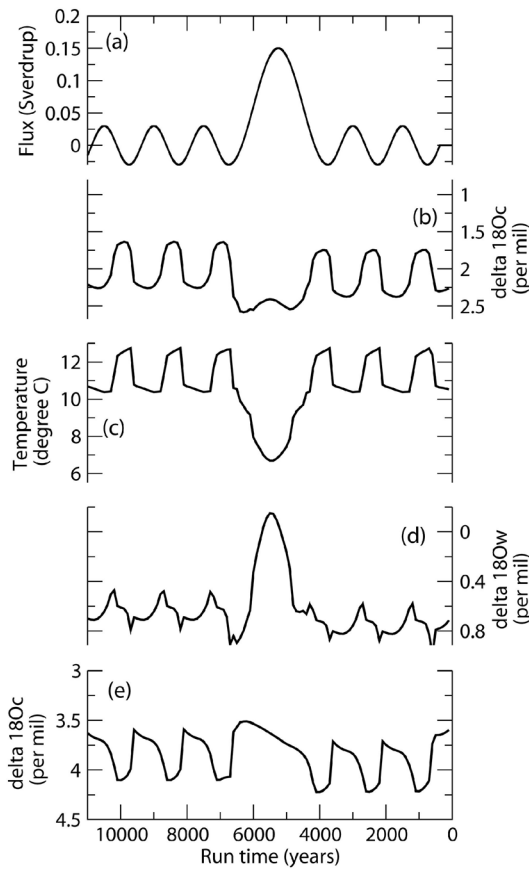


Fig. 1. Scenario and model output for the D/O events and HEs. (a) Anomalous freshwater flux scenario in Sverdrup ( $10^6 \text{ m}^3 \text{ s}^{-1}$ ). All model outputs are shown at  $41.25^\circ\text{N}$  in the Atlantic basin to be compared with the core MD95-2042. (b) Simulated  $\delta^{18}\text{O}$  of the calcite for the surface layer that is the first 50 m of the model (in per mil vs. SMOW). (c) Temperature evolution in the model for the surface layer (in  $^\circ\text{C}$ ). (d) Simulated evolution of the  $\delta^{18}\text{O}$  of the water for the surface layer (in  $\text{‰}$  vs. SMOW). (e) Simulated  $\delta^{18}\text{O}$  of the calcite at 3000-m depth. Results in temperature and  $\delta^{18}\text{O}$  of the water are not shown for the depth 3000-m as they look similar and contribute for half the amplitude each, see text for discussion.

Fig. 1. Scénario et résultats du modèle pour les événements de D/O et de Heinrich. (a) Scénario en flux d'eau douce ajouté en Sverdrup ( $10^6 \text{ m}^3 \text{ s}^{-1}$ ). Toutes les sorties du modèle sont données à  $41.25^\circ\text{N}$  dans l'Atlantique pour une comparaison aisée avec la carotte MD95-2042. (b)  $\delta^{18}\text{O}$  de la calcite pour le niveau de surface du modèle, i.e. les 50 premiers mètres (exprimé en pour mille versus SMOW). (c) Évolution de la température dans le modèle pour le niveau de surface (en  $^\circ\text{C}$ ). (d) Résultats de la simulation en  $\delta^{18}\text{O}$  de l'eau (en pour mille versus SMOW). (e)  $\delta^{18}\text{O}$  de la calcite simulée pour une profondeur de 3000-m. Les résultats pour la température et le  $\delta^{18}\text{O}$  de l'eau ne sont pas inclus ici, car leurs variations sont dans le même sens et contribuent chacun pour la moitié du signal en  $\delta^{18}\text{O}$  de la calcite.

events, we decided not to give a specific  $^{18}\text{O}$  signature to the flux associated with these events. One would need to understand the process correctly to apply the appropriate value. Besides, the D/O events are recognized to be mainly a temperature signal both from ice cores and sediment cores. If it is indeed the case, then we should be able to reproduce correctly the temperature and the oxygen-18 signal without any specific isotopic content for the additional freshwater flux. As for the HEs, we already stated that the mechanism involved is the melting of numerous icebergs in the North Atlantic. The ice-sheets of the last glacial period are known to have a much depleted content in the oxygen-18 of the ice. This means that the water associated with the melting of icebergs should have also a much depleted content. We are using here a value of  $-30\text{‰}$ , typical of low-altitude Greenland ice cores (e.g., in [7]).

### 3. Model results

Results of the model integration are shown in Fig. 1 for the Atlantic basin at  $40^\circ\text{N}$ . The oxygen-18 for calcite of the surface layer and at depth (3000 meters deep) is shown on panels (b) and (e), respectively. Results are expressed in standard delta notation defined as follows:

$$\delta^{18}\text{O} = \left( \frac{R_{\text{measured}}^{18/16}}{R_{\text{std}}^{18/16}} - 1 \right) \times 1000$$

where  $R_{\text{std}}$  is the standard  $^{18}\text{O}/^{16}\text{O}$  ratio. The  $\delta^{18}\text{O}$  signal for the calcite depends both from temperature and  $\delta^{18}\text{O}$  of the water in which it precipitates. We use here the classical formula established by [10,18], as follows:

$$\delta^{18}\text{O}_c = 21.9 + \delta^{18}\text{O}_w - \sqrt{310.61 + 10T}$$

where  $T$  is the temperature expressed in Celsius and  $\delta^{18}\text{O}_w$  is the oxygen-18 of the water, expressed in per mil versus SMOW. To better understand the variations seen in the  $\delta^{18}\text{O}$  of the calcite, we are showing also the temperature and  $\delta^{18}\text{O}$  of the water in panels (c) and (d) in Fig. 1. The scale in this figure is such that by adding 'by eye' the temperature and the  $\delta^{18}\text{O}_w$  together, one can obtain directly the  $\delta^{18}\text{O}_c$ . From the surface signals of Fig. 1, we can first note that the origin of the simulated  $\delta^{18}\text{O}_c$  signal is different during D/O events and

during HEs. During D/O events, the signal is mainly due to temperature changes: oscillations of about  $2^{\circ}\text{C}$  imprint the  $\delta^{18}\text{O}_c$  variations by  $0.5\text{‰}$ . At the same time, some small variations related to changes in surface conditions can be seen (changes in advected  $\delta^{18}\text{O}$  of surface waters essentially) of about  $0.1\text{‰}$ . Interpreting the surface  $\delta^{18}\text{O}_c$  signal during D/O events as a temperature signal seems then to be valid in our model. During the simulated HE, the picture is different: the  $\delta^{18}\text{O}_c$  signal is a composite of partially opposite temperature and  $\delta^{18}\text{O}_w$  variations. At the peak of the simulated HE, the strong  $6\text{-}^{\circ}\text{C}$  cooling signal is modified by a  $0.9\text{‰}$  decrease in  $\delta^{18}\text{O}_w$ , produced by the advection of the melting signal at this site. This explains that the increase in  $\delta^{18}\text{O}_c$  is smaller than expected from the temperature signal alone (which would produce  $\sim 1.5\text{‰}$  increase in  $\delta^{18}\text{O}_c$ ). The  $\delta^{18}\text{O}_c$  signal simulated at depth shows a decrease when the surface is showing higher values and an increase when the surface shows lower values during D/O events. As for the surface, the signal is in part due to temperature changes and in part due to changes in  $\delta^{18}\text{O}$  of the water. During D/O events, the  $\sim 0.5\text{‰}$  change in calcite  $\delta^{18}\text{O}$  is due to a warming of up to  $2^{\circ}\text{C}$  (inducing a  $-0.5\text{‰}$  signal in  $\delta^{18}\text{O}_c$ ) of the deep waters, together with a  $-0.15\text{‰}$  change in  $\delta^{18}\text{O}$  of waters, but not in phase. This warming occurs at time of positive fresh-water input in the scenario. This leads to a decrease in the THC, decreasing advection of cold waters to the deep site. The site is then more influenced by diffusion from the warmer oceanic layer above it and warms up. The warming is stopped when the THC re-accelerate. During the HE the same mechanism occur but with a slightly stronger signal in  $\delta^{18}\text{O}_w$ : the northern melting signal is advected to the site at the end of the HE and produces a  $0.5\text{‰}$  decrease in  $\delta^{18}\text{O}_w$ . The end of the warmer period is reached at the same time (due to the restart of the THC) compensating, in the  $\delta^{18}\text{O}_c$  signal, the decrease in  $\delta^{18}\text{O}_w$ . This mechanism explains that the amplitude of the deep  $\delta^{18}\text{O}_c$  signal seen in panel (e) of Fig. 1 is about the same during an HE and during D/O events, although the relative amplitude of the  $\delta^{18}\text{O}_w$  and temperature signals are quite different. This shows the usefulness of simulating the  $\delta^{18}\text{O}$  in models to unravel the relative effect of temperature and  $\delta^{18}\text{O}$  of waters in the  $\delta^{18}\text{O}_c$  signal.

#### 4. Model to data comparison

Comparison between the results of our simulation and the  $\delta^{18}\text{O}_c$  data of the core MD95-2042 [19] is shown in Fig. 2. The sediment core record is on its own depth scale. At first glance, and apart from some variability in the record that we do not reproduce, our

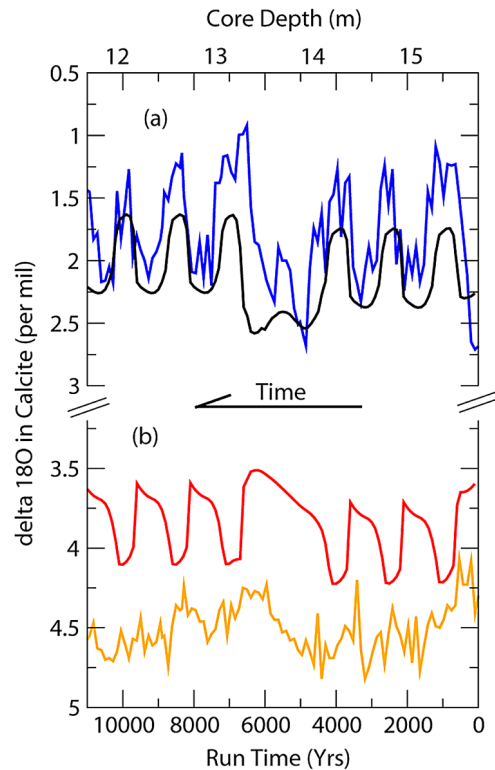


Fig. 2. Model–data comparison in  $\delta^{18}\text{O}_c$ . (a)  $\delta^{18}\text{O}_c$  computed in the first layer of the model (lower curve) compared to the planktic record of Shackleton et al. [19] (upper curve). (b)  $\delta^{18}\text{O}_c$  computed in the model at 3000-m depth (upper line) compared to the benthic of the same core (lower line). The top horizontal axis shows the record versus the core depth, whereas the bottom horizontal one shows it versus the model time.

Fig. 2. Comparaison données–modèle en  $\delta^{18}\text{O}$  de la calcite. (a)  $\delta^{18}\text{O}$  de la calcite calculé dans le premier niveau du modèle (50 premiers mètres, courbe du bas) ainsi que le  $\delta^{18}\text{O}$  de la calcite provenant de l’enregistrement planctonique de la carotte MD95-2042 (courbe du haut). (b)  $\delta^{18}\text{O}$  de la calcite calculée dans le modèle à 3000 m de fond (courbe du haut) ainsi que l’enregistrement benthique de la carotte MD95-2042 (courbe du bas). L’axe des abscisses supérieur est gradué en profondeur dans la carotte de sédiments, tandis que l’axe des abscisses inférieur est gradué en fonction du temps de simulation.



results agree fairly well with the sediment record. One feature we miss to reproduce here is the correct absolute value at depth (benthics). Where our model produces a calcite  $\delta^{18}\text{O}$  signal between 3.5 and 4.2‰, the benthic  $\delta^{18}\text{O}$  record exhibits values between 4.25 and 4.75‰. There are potentially two reasons for this mismatch: (1) as was already noted by [15], the model might not be cold enough in the deep during glacial times that translate into too light isotopic values for the simulated calcite; (2) we did not add a global  $^{18}\text{O}$  shift to account for ice-sheet build-up with low oxygen-18 content. At the Last Glacial Maximum (LGM), this enrichment is of 1.2‰ [3]. It is however difficult to assess what was the value of this enrichment in the time frame we are looking at here (40-kyr BP). Northern hemisphere ice-sheets were about half the size of the LGM ones, but there is no obvious reason for this enrichment to be linear with the size of ice-sheets [9]. Therefore, the shift here could be anything between 0.3 and 0.8‰. When thinking in terms of relative values, the amplitudes simulated here are in very good agreement with data for the planktic signal and somewhat overestimated for the benthics, this latter both for the D/O events and HE (by at least 0.2‰). This mismatch at depth suggests that we miss or represent incorrectly some process(es). Looking back at the relative importance of the temperature and  $\delta^{18}\text{O}_w$  signals, it seems plausible that the diffusion of warmer waters to the deep when the THC slows down is overestimated and that the effect on temperature should be smaller (by 1 °C to match the data record). Some data are also suggesting that the temperature could actually be colder during HE [20]. An interesting feature seen in Fig. 2 is the relative maximum seen in the record of planktonic foraminifera during the HE. The modelled signal also presents such a relative maximum, although weaker than in the sediment record. As was discussed in Section 3, this relative maximum is, in the model, the imprint of the  $\delta^{18}\text{O}_w$  melting signal of North Atlantic, advected to the site. It is tempting to interpret the sediment record as such. To try to match the amplitude of the relative maximum of the data record, we tried some experiments with a stronger freshwater flux during HE (not shown). However, this does not modify the obtained result, since much of the added freshwater goes northward in the Arctic. To obtain better amplitude of this signal, one would then need to apply the meltwater signal more to the south,

around the IRD belt. The mapping of the surface  $\delta^{18}\text{O}_c$  anomaly during the HE4 [2] shows indeed that a low  $^{18}\text{O}$  anomaly – logically associated with the melting of icebergs – exists in this region. This implies in turn that the melting of icebergs did occur around 45 to 55°N and that applying the freshwater flux more to the north (e.g., 60°N in the scenario used here) is inconsistent with the data.

## 5. Conclusions

Comparing  $\delta^{18}\text{O}_c$  data from a sediment core and the output of a coupled climate model including the oxygen-18 for a period of time covering the HE4 and the surrounding D/O events provide insights into the interpretation of the sediment core record and the setting of the model experiment. We showed here that (1) assuming that there was no additional  $^{18}\text{O}$  flux to the ocean at the time of D/O events enables a favourable comparison with the data record, suggesting that the planktic record is showing essentially a temperature signal – the cause of these events remains unclear, but the implication of this absence of strong  $^{18}\text{O}$  signal seems to rule out considerable melting from ice-sheets – and (2) that using a meltwater flux for Heinrich Events in another location than the IRD belt leads to a mismatch with the palaeorecord we compared to. The interpretation of the relative maximum in the planktic record at time of HE4 needs also to be confirmed by looking for this signal in other sediment cores in the North Atlantic. There is also indication that the model in its current setting might overestimate the vertical diffusivity in the deep ocean, leading to a mismatch with the benthic data record. This would need to be tested by comparing with other benthic records to assure that we indeed capture the correct mechanism. This first study demonstrates the validity of the method for improving both model scenarios and comprehension of the sediment core records. It will need to be pursued by extensive comparison to other sediment core records to draw better conclusions for the whole North Atlantic.

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