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The Last Glacial Maximum and Heinrich Event 1 in terms of climate and vegetation around the Alboran Sea: a preliminary model-data comparison

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Abstract

The Heinrich Event 1, the most recent of the glacial North Atlantic large iceberg discharges, is well documented in continental and marine records, but this large perturbation of the climate system has rarely been simulated. Here we propose a preliminary model-data comparison for this period, which we compare to the Last Glacial Maximum state. The pollen record from one specific core from the western Mediterranean Sea (ODP site 976) is analysed both in terms of vegetation distribution and climatic implication. The climate and vegetation of both periods are then simulated and compared to the pollen-based data. ***To cite this article: M. Kageyama et al., C. R. Geoscience 337 (2005).***

Résumé

Le dernier maximum glaciaire et l'événement de Heinrich 1 en termes de climat et de végétation autour de la mer d'Alboran : une comparaison préliminaire entre modèles et données. L'événement de Heinrich 1, la plus récente des grandes débâcles glaciaires dans l'Atlantique nord, est bien documenté dans de nombreux enregistrements continentaux et marins, mais cette perturbation importante du système climatique a rarement été simulée. Nous proposons ici une comparaison préliminaire entre modèles et données pour cette période, que nous comparons au dernier maximum glaciaire. L'enregistrement pollinique d'une carotte de la Méditerranée occidentale est analysé en terme de végétation et de climat. Les résultats de simulations de

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climat et de végétation pour chaque période sont comparés à ces reconstructions. ***Pour citer cet article : M. Kageyama et al., C. R. Geoscience 337 (2005).***

Keywords: Heinrich 1; Last Glacial Maximum; Europe and western Mediterranean Sea; Pollen record; Climatic reconstruction; Atmospheric General Circulation Model with high resolution model over Europe; Dynamical Global Vegetation Model

Mots-clés : Heinrich 1 ; Dernier maximum glaciaire ; Europe et Méditerranée occidentale ; Enregistrement pollinique ; Reconstruction climatique ; Modèle de circulation générale atmosphérique haute résolution sur l'Europe ; Modèle global de végétation dynamique

Version française abrégée

La dernière période glaciaire (10–90 ky BP) est régulièrement marquée par des changements climatiques abrupts, tels que les événements de Heinrich [13], qui correspondent à des grandes débâcles d'icebergs provenant des inlandsis bordant l'Atlantique nord, et en particulier de la calotte nord-américaine. Les variations climatiques liées à un événement de Heinrich sont rapides (quelques dizaines d'années [5]) et importantes, à la fois en termes de température et de cycle hydrologique (voir [12] pour une revue récente). L'étude des assemblages polliniques conservés dans les sédiments marins a montré que des changements de végétation majeurs ont lieu en même temps que les bouleversements océaniques liés à l'apport d'eau douce par les icebergs pendant les événements de Heinrich [8,28]. Nous analysons ici l'enregistrement provenant du site ODP 976 situé en mer d'Alboran (Méditerranée occidentale), pour la période couvrant le dernier maximum glaciaire (LGM, *Last Glacial Maximum*, ∼21 ka BP) et l'événement de Heinrich 1 (H1, ∼15 ka BP). Pendant le maximum glaciaire, la végétation est dominée par les Ericaceae associées à des Herbacées et à des arbres de la forêt d'altitude (*Cedrus*), tandis que pendant l'événement H1, le semi-désert à *Artemisia* se développe aux dépens des autres formations végétales arborées et herbacées (Fig. 1). Ces modifications de la végétation s'effectueraient en moins de 500 ans, d'après notre modèle d'âge. Ces résultats ont été interprétés en termes climatiques à travers une reconstruction, basée sur la méthode des meilleurs analogues [11], de la température du mois le plus froid (MTCO) et de la moyenne des précipitations annuelles (Pann). Pendant le dernier maximum glaciaire, la température du mois le plus froid et les précipitations annuelles apparaissent proches de la période actuelle, ce qui peut être expliqué par une absence d'analogue dans la base de données actuelle, comme le montre l'indice de similarité entre échantillons fossiles et analogues actuels (10^{e} courbe, Fig. 1). Par contre, d'après les données polliniques obtenues sur l'événement H1, les reconstitutions climatiques montrent des températures du mois le plus froid, de 5 à 15 °C plus basses qu'au cours du LGM, avec des précipitations annuelles diminuées de moitié. Les diminutions de température sont légèrement supérieures à celles obtenues pour les températures de surface en mer Méditerranée (5–10 °C) [6] et pour des températures du mois le plus froid, déduites des associations végétales dans les sédiments lacustres [1,31].

L'exemple de cet enregistrement montre que le climat et la végétation de la période de l'événement de Heinrich 1 sont bien documentés, l'analyse de pollens provenant d'un enregistrement marin permettant de lever les doutes sur la chronologie des événements continentaux par rapport à la perturbation initiale de l'océan Atlantique nord. Cet événement constitue dès lors un bon test de nos capacités à simuler les changements climatiques abrupts et leurs conséquences sur la végétation. Nous avons effectué des simulations climatiques pour la période du dernier maximum glaciaire et pour la période de l'événement de Heinrich 1, que nous considérons ici comme une perturbation du système climatique au dernier maximum glaciaire. Ces simulations ont été effectuées à l'aide du modèle de circulation générale atmosphérique (AGCM) LMDZ.3.3 (développé au Laboratoire de météorologie dynamique), avec une grille affinée sur l'Europe (60 km de résolution). Cette grille, fine sur l'Europe (voir Fig. 2c–f) et lâche aux antipodes, permet une meilleure prise en compte de l'influence des caractéristiques de la surface dans la région européenne, en particulier pour ce qui concerne l'orographie et les définitions des côtes. Ce modèle a été utilisé pour une simulation du climat du dernier maximum glaciaire et comparé, pour ce cas, à d'autres modèles ayant une résolution fine sur l'Europe [15]. Le climat du dernier maximum glaciaire est obtenu en suivant le protocole défini par le projet PMIP (*Paleoclimate Modelling Intercomparison Project*, [16]) : température de surface des océans, telle que reconstruite par le projet CLIMAP [7], reconstruction des calottes glaciaires de Peltier [22], concentration en CO_2 fixée à 185 ppm [23] et paramètres orbitaux d'il y a 21 000 ans [4]. La simulation climatique pour l'événement de Heinrich 1 est obtenue en modifiant une seule de ces conditions aux limites : les températures de surface de l'Atlantique nord. Dans un premier temps et pour cette expérience préliminaire, nous avons choisi d'imposer une anomalie froide de SST tout au long de l'année atteignant 4 °C entre 40 et 50°N, s'estompant vers le pôle Nord vers le nord et à 32°N vers le sud. Lorsque la nouvelle température de surface océanique calculée selon ce protocole est inférieure à $-1{,}8$ °C, le type de surface du point de grille devient de la banquise. Aucune anomalie n'a été imposée en mer Méditerranée dans cette expérience idéalisée. La durée de chaque expérience est de 11 ans, les moyennes climatologiques étant effectuées sur les 10 dernières années des simulations. Les résultats de ce modèle ont ensuite été utilisés pour forcer le modèle global de végétation dynamique (DGVM) ORCHIDEE [17], afin d'obtenir la végétation à l'équilibre avec le climat de chaque période.

Les températures du mois le plus froid, simulées pour H1, sont inférieures de plus de 4 °C à celles simulées pour le LGM dans le golfe de Gascogne, car ce dernier est partiellement couvert de banquise dans la simulation H1. Ce refroidissement significatif ne se propage pas loin à l'intérieur des terres : la différence de température est nulle à l'est du Massif central en France, et sur le Sud-Est de la péninsule Ibérique (Fig. 2a). Ceci est surprenant au regard d'expériences où une anomalie chaude avait été appliquée sur l'Atlantique nord à partir d'une simulation glaciaire [25], où l'anomalie de température se propageait beaucoup plus à l'intérieur des terres. Ces résultats ayant été obtenus à l'aide de modèles différents, il sera intéressant de mener le même type d'expérience en utilisant le même modèle pour évaluer les asymétries de la réponse climatique à de tels changements de température de surface en Atlantique nord. Nos résultats montrent également combien il sera important, dans de futures expériences numériques, d'imposer des anomalies de températures de surface correspondant à H1 sur la mer Méditerranée, de manière à obtenir des simulations qui soient plus réalistes et plus comparables aux données.

Le cycle hydrologique est plus profondément affecté par l'anomalie froide de température de surface de l'Atlantique nord : la précipitation diminue de 20 % dans la simulation H1 par rapport à celle du LGM sur toute la façade Atlantique et sur la majeure partie de la péninsule ibérique (Fig. 2b), pour les latitudes comprises entre 37 et 49°N. En revanche, les précipitations augmentent sur la Méditerranée orientale, mais ce résultat devra être réévalué dans une simulation où les SST méditerranéennes seront modifiées pour H1. Les résultats obtenus sur la péninsule ibérique semblent cependant prometteurs, car d'un ordre de grandeur tout à fait comparable aux reconstructions polliniques.

Les conséquences de ces changements climatiques sur la végétation sont importantes, notamment en terme de surface couverte par de la végétation et de couverture forestière, qui décroissent pour la période H1 (Fig. 2d et f), montrant que la végétation glaciaire est proche de seuils climatiques. La comparaison aux assemblages polliniques est favorable, mais souffre de la difficulté à associer certains taxons aux catégories du modèle.

Les perspectives de ce travail préliminaire sont nombreuses : pour les reconstructions, il s'agira de rassembler les enregistrements de cette période situés en Europe de l'Ouest et sur le pourtour méditerranéen et de les traiter uniformément pour obtenir des reconstructions de végétation et de climat. Les efforts de modélisation devront porter sur la modélisation du système couplé atmosphère-océan-végétation en période glaciaire et de sa réaction à un apport d'eau douce massif en Atlantique nord. D'autre part, il serait intéressant de mener des expériences plus réalistes, incluant notamment les changements de température de surface en Méditerranée, en utilisant les mêmes méthodes que celles présentées ici. Finalement, il pourra aussi être profitable, pour faciliter la comparaison aux données polliniques, de distinguer davantage de types de végétation dans le modèle global de végétation dynamique.

1. Introduction

The last glacial period (10–90 ky BP) is marked by abrupt and regular climatic changes. Among these, Heinrich Events [13] correlate with massive iceberg discharges from the North Atlantic ice-sheets and particularly from the Laurentide ice-sheet. The climatic changes related to Heinrich Events are large, both in terms of temperature and hydrological cycle (for a recent review, see [12]), and occur in a matter of a few tens of years [5]. During these events, major vegetation distribution changes occur, simultaneous to shifts in the ocean state (surface temperature, circulation), according to the study of pollen assemblages within marine cores [8,28].

Only few simulations of the climate during a Heinrich Event [3,14] have been performed and none have investigated its impact on the vegetation. Heinrich Event 1 (H1, ca. 15 ky BP), the most recent and best-documented of the Heinrich Events, constitutes a good test to evaluate the models' capability to reproduce abrupt climate and vegetation changes. So far, modelling studies have mainly focussed on the Last Glacial Maximum (LGM, ca. 21 ky BP) climate, as for instance in the on-going PMIP project (Paleoclimate Modelling Intercomparison Project, [16]). To our knowledge, the climate and vegetation of Heinrich Event 1, which represents a perturbation of this glacial state and the beginning of the deglaciation process, has not been simulated using a general circulation model. Its regional impact on Europe is documented through a number of records, but has not been simulated either. This paper represents a first attempt of a model-data comparison over western Europe for the period of Heinrich Event 1. The largest sea surface temperature and sea–ice cover perturbation related to H1, compared to the LGM, occurs over the mid-latitude North Atlantic. We therefore expect the response to this perturbation to be largest on the European Atlantic coast. However, in this preliminary study, we focus on the western Mediterranean Sea, where our reference marine core (ODP site 976 in the Alboran Sea) is situated, and which is very near the Gibraltar strait. Studying a pollen sequence from such a marine core benefits from the perfect correlation to ocean variations and therefore from a consistent chronology compared to other records [8,28]. A quantitative estimate of the temperatures and precipitation is obtained through the best-analogue method [10] applied to the pollen assemblages. We use the atmospheric general circulation model LMDZ.3.3 with a fine grid over Europe to simulate the climates of the LGM and H1 periods. We simulate the vegetation for these two periods by forcing a dynamical global vegetation model with the climatic outputs from the atmospheric general circulation model. We then compare the climate and vegetation from model and data.

2. Climatic reconstructions from the Last Glacial Maximum to the beginning of the Bolling-Allerod from core ODP site 976

We present the pollen analyses of the interval 14–21.5 kyr in a marine core, ODP Site 976 (36°12′N, 4°18′W, 1108 m water depth), drilled in the Alboran Sea, the westernmost basin of the Mediterranean Sea. The chronology of this part of the core is based on AMS radiocarbon ages [8] and has been refined by correlation between the temperate species pollen curve and the NGRIP isotopic record [18,19]. Pollen methodology follows a classic protocol already developed by Combourieu Nebout et al. [8]. Palaeoenvironmental interpretation of the pollen assemblage fluctuations is based on the assumption that the primary pollen contribution to Alboran Sea sediments comes from west Mediterranean borderlands and that pollen in ocean sediments, carried by winds and rivers, reflects the regional vegetation in the nearby continental areas and thus the environmental parameters which determine the vegetation.

Modern environments follow the classic Mediterranean scheme of the vegetation in superimposed belts from lowlands to the summit of mountains [21,27]. The present-day Mediterranean climate is characterised with long dry summers and mild rainy winters [30]. The fossil pollen spectrum ranges from semi-desert to mountain deciduous and coniferous forest ones. Interpretation of the pollen spectrum follows the modern climatic-plant relationships in Europe and Northern Africa [24,33]. Here, the pollen percentages are represented in a simplified pollen diagram which expresses the variations of the main taxa and vegetation associations (*Pinus*; Altitudinal plants as *Abies* and *Cedrus*; temperate association composed of Eurosiberian trees like *Quercus*, *Fagus*, *Carpinus*, *Corylus*, *Alnus*, *Betula*, *Tilia*, *Ulmus*, ...; Ericaceae; Mediterranean plants as *Quercus ilex*, *Olea*, ...; semi-desert plants composed of *Artemisia*, Amaranthaceae-Chenopodiaceae and *Ephedra*; herbaceous plants as Asteraceae, Poaceae, Caryophyllaceae, Brassicaceae, ...).

The best analogue method has been applied to the ODP fossil assemblage to provide a quantitative estimate of paleotemperatures and paleoprecipitation [10]. In the best modern analogue method [11], a dissimilarity index between each fossil sample and ten best modern analogues is calculated by a chord distance, i.e. a sum of difference between square root-transformed percentages of the 103 selected taxa. The reconstruction values are given by the weighted mean of the climate of these analogues according to the inverse chord distance, and the error is defined as the lower and the upper extreme climate among the ten analogues. The method, first developed on continental series, is based on 1512 modern pollen spectra from the Mediterranean basin and Eurasia. As *Pinus* is always over-represented in marine sediments, we removed this taxon from the modern spectra as well as from the fossil spectra. In this work we only present the estimates of two climatic parameters, the annual precipitation (Pann) and the mean temperature of the coldest month (MTCO).

The pollen diagram shows a large contrast between the Last Glacial Maximum (LGM) and the H1 phase as already evidenced for all the Heinrich Events in marine cores [8,28] as well as in continental ones [1,26,31,32]. During the LGM, Ericaceae are well developed associated to herbaceous plants and altitudinal forest (*Cedrus*). They indicate that, at least in the mountains, temperature and climate must be cold and humid. Nevertheless climatic parameters deduced from pollen analyses reveal mean annual precipitation and temperature of the coldest month not so different from present-day ones. These discrepancies can be explained by a lack of good analogues in the modern pollen database as shown by LGM high distances (Fig. 1).

During the H1 period, semi-desert plants are well developed while other plants (altitudinal trees, Ericaceae and temperate trees) are very weakly represented. Such an association indicates a strong decrease in temperature and enhanced dryness. This conclusion is confirmed by the pollen based climatic estimates, which indicates a decrease of at least 200 mm in mean annual precipitation (a relative change of ∼50% compared to LGM values) and of 5 to 15 °C in temperature of the coldest month. Such a decrease has been observed in other records in Alboran Sea and off Portugal for Heinrich Events 3 to 5 [28] and in continental series in Lago Grande di Monticchio, Italy [1]. It remains slightly higher than the sea surface temperature changes (5–10 °C) obtained from alkenones in the Alboran Sea [6] and the temperature of the coldest month deduced from the Monticchio record (ca. 7 °C) for the studied period [1].

The transition observed in the pollen diagram between the LGM and H1 pollen assemblages occurs in less than 500 years, according to our age model. However, it seems that even small changes in vegetation such as those occurring at the beginning of the transition results in rapid changes in the mean annual precipitation. On the other hand, the reconstructed temperature of the coldest month cools more progressively.

3. Design of the numerical experiments

The numerical experiments all use the LMDZ.3.3 atmospheric general circulation model in a version with a stretched grid and therefore finer resolution (down to 60 km) over Europe. In a previous work, this model has been used for the simulation of the LGM climate and compared to two other high-resolution models [15]. In the present study, we obtain the vegetation distribution consistent with the climate simulated by our atmospheric general circulation model by forcing the Dynamical Global Vegetation Model ORCHIDEE [17] with the climate obtained with LMDZ.3.3. Natural vegetation in ORCHIDEE results from the competition between 10 plant functional types (PFTs): tropical broad-leaved evergreen, tropical broad-leaved raingreen, temperate needle-leaf evergreen, temperate broad-leaved evergreen, temperate broad-leaved summergreen, boreal needle-leaf evergreen, boreal broad-leaved summergreen, needleleaf summergreen, C3 grass, C4 grass. These Plant Functional Types, plus bare soil, can co-exist within one model grid-cell. We will therefore show the fraction of arboreal Plant Functional Types (sum of the arboreal Plant Functional Type fractions) vs. herbaceous

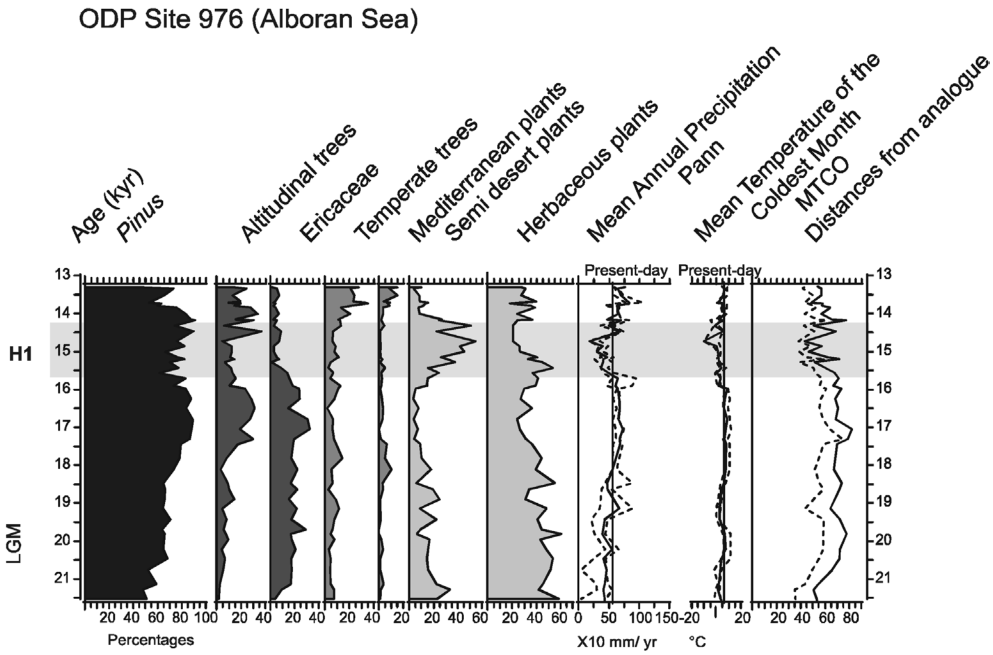

Fig. 1. First 7 curves: simplified pollen diagram for ODP site 976. Percentages for taxa other than *Pinus* are computed from a pollen sum excluding *Pinus*. Curves 8 and 9: Reconstruction of the annual precipitation and mean temperature of the coldest month. Dotted curves indicate minimum and maximum reconstructions. Last curve: Similarity index (Chord distance) measuring the quality of the modern analogues. The figure shows the calculated distance of the first (dotted line) and the last (solid line) of the best analogues selected.

Fig. 1. 7 premières courbes : diagramme pollinique simplifié du site ODP 976. Les pourcentages pour les taxa autres que *Pinus* sont calculés sur une somme pollinique excluant *Pinus*. 8^{e} et 9^{e} courbes : Reconstructions de la précipitation annuelle et de la température du mois le plus froid. Les courbes en pointillé correspondent aux reconstructions minimales et maximales. 10^{e} courbe : Indice de similarité mesurant la qualité des analogues actuels : distances au premier (pointillés) et dernier (trait plein) meilleurs analogues sélectionnés.

Plant Functional Types (sum of the C3 and C4 grass Plant Functional Types).

We have run two climatic simulations, for the time slice of the Last Glacial Maximum and that of Heinrich Event 1. To simplify the experimental design and better distinguish the response of the climate and vegetation to the sole North-Atlantic sea surface temperature differences associated with H1, both simulations use the same forcings except for these North Atlantic sea surface temperatures (SSTs). Hence, both experiments are forced by the 21 ky BP orbital parameters [4] and CO_2 [23] and 21 ky BP ice-sheets as reconstructed by Peltier [22]. Following the PMIP (Paleoclimate Modelling Intercomparison Project [16]) recommendations, the LGM prescribed SSTs are from the CLIMAP reconstructions [7]. The H1 climate is obtained by lowering the SSTs by up to 4 °C over the North Atlantic, between 40° and 50°N. The imposed SST anomaly decreases linearly to 0 °C at 32°N to the south and equals 3 °C between 50° and 54°N, 2 °C between 54 and 60°N, and 1 °C towards the North pole. This SST anomaly is idealised given the few SST reconstructions that are available, e.g. [2,29]. Its latitudinal location corresponds to the latitudes of the anomalies observed for Heinrich Events (see for instance Ref. [9]). The sea–ice cover is adjusted to these new SSTs by imposing sea-ice cover when and where the SST is below −1.8 °C. The atmospheric general circulation model is run with each set of boundary conditions for 11 years. The climatological averages are computed from the last ten years of the simulations.

The numerical experiments are therefore designed to test the sensitivity of the glacial climate to a drastic cooling in the mid-latitude North Atlantic temperatures. The use of the Dynamical Global Vegetation Model ORCHIDEE allows a quantification of the consequences of this cooling in terms of vegetation changes: each climatic simulation, LGM and

H1, yields a forcing for ORCHIDEE which produces a Plant Functional Type distribution for each of the time slices. The off-line forcing for ORCHIDEE is obtained by calculating the monthly anomalies between the simulated paleoclimates and the results of a present-day control simulation, carried out with the same version of LMDZ. These anomalies are then added to a present-day observed climatology [20]. The resulting monthly fields are then fed into a weather generator which produces high frequency forcing data for ORCHIDEE [17]. Hence our experimental design does not account for the impact of the LGM and H1 vegetations on the climate. Its assessment is left for further studies.

The numerical experiments have been designed as simple as possible. Our goal in the present work is to perform a preliminary analysis of the sensitivity of the atmospheric model LMDZ.3.3 and vegetation model ORCHIDEE and to compare it to an example of an available reconstruction of the climatic and vegetation changes related to H1, to assess whether the model can reproduce the amplitude of H1 depicted by the pollen record.

4. Model-data comparison

4.1. *Temperature of the coldest month*

Fig. 2a shows the difference between LGM and H1 in the temperature of the coldest month computed by the model. This temperature is computed as the coldest 2 m air temperature in the climatological seasonal cycle, for each grid point. The imposed anomaly pattern is clearly visible over the North Atlantic, with H1 being colder than LGM by more than 3 °C North of 40°N. The difference in air temperature is significantly larger than 4 °C over regions where lowering the sea surface temperatures implied sea-ice formation, as in the Bay of Biscay. Given the general atmospheric circulation pattern over western Europe in winter, consisting of strong westerlies, especially in the LGM climate [15], it is surprising that the imposed temperature anomaly does not have a large impact inland. Indeed, there is no significant decrease in the temperature of the coldest month in the H1 simulation, compared to the LGM in southeastern Iberia, nor in central and eastern France (see the position of the thick contour on Fig. 2). This is all the more surprising since previous studies (using different models), in which a warm sea surface temperature anomaly was imposed in the North Atlantic in an LGM situation, lead to significant changes inland [25]. The asymmetry of the atmospheric response to a positive vs. a negative anomaly should be investigated by using the same model. It is possible that the fact that our LGM climate is obtained by prescribing the CLIMAP sea surface temperatures [7], i.e. cold conditions, explains the weak temperature response to an additional cold anomaly.

The temperature of the coldest month around the Alboran Sea does not cool in the H1 simulation compared to LGM, while the palynological reconstruction from Section 2 yields a 5 to 15 °C decrease. This clear discrepancy between model and data can partly be assigned to the fact that our experimental design lacked the treatment of the Mediterranean surface temperatures. Reconstructions based on alkenones show that western Mediterranean surface temperatures during H1 could have been lowered by 5 to 10 °C compared to their LGM values [6]. A future, more realistic, experiment, will have to make hypotheses on sea surface temperature changes for the Mediterranean Sea using this type of information.

4.2. *Annual precipitation*

From LGM to H1, annual precipitation (Fig. 2b) decreases over the North Atlantic ocean, most of Iberia and France by as much as 30%. On the other hand, it increases by as much as 20% over the western Mediterranean Sea. Nevertheless, the averaged precipitation over the region draining into the Alboran Sea (southern Spain, northern Morocco) decreases in H1 compared to LGM. Over Iberia, the relative precipitation decrease is of the same order of magnitude as the one deduced from the pollen record. The increase over the western Mediterranean Sea could be due to the fact that we have not imposed an SST anomaly over the Mediterranean Sea in the H1 experiment. Nevertheless, our experiments show that imposing an SST anomaly over the North Atlantic results in a significant decrease in precipitation over Iberia and France. The response in the hydrological cycle is therefore larger than the thermal response.

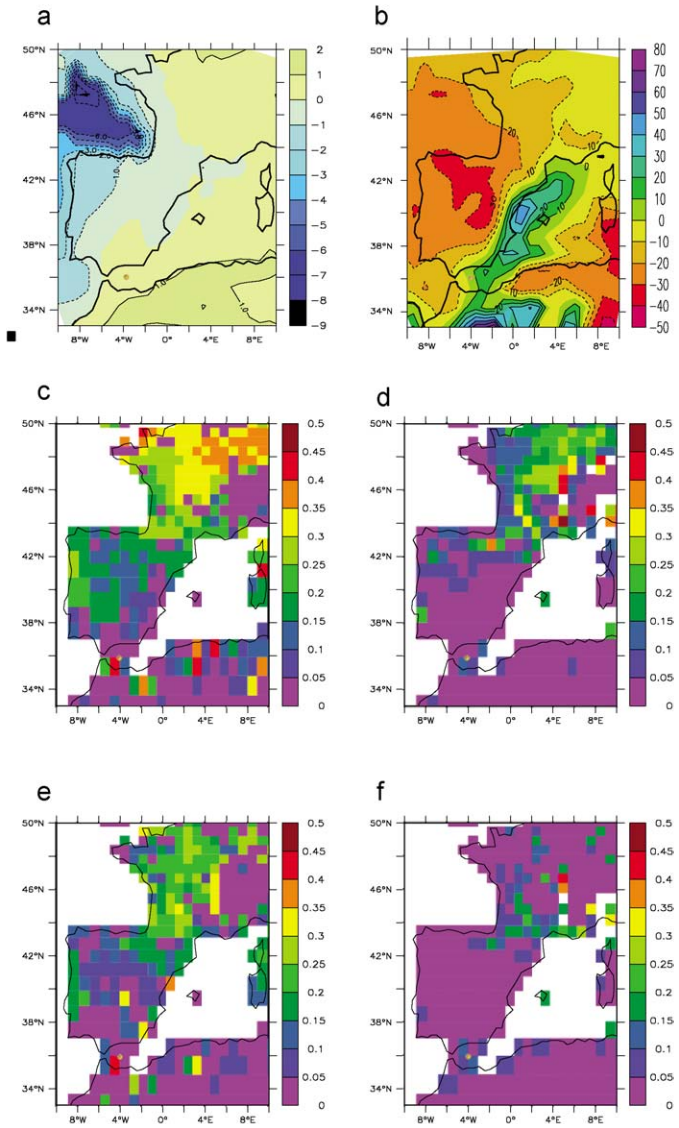

Fig. 2. (**a**) Difference (LGM–H1) in the simulated temperature of the coldest month (°C); (**b**) annual precipitation difference H1–LGM normalised by the LGM value (in %); (**c**)–(**f**) simulated grass and tree fractions for the LGM and H1 experiments: (**c**) LGM grass fraction, (**d**) LGM arboreal fraction, (**e**) H1 grass fraction, (**f**) H1 arboreal fraction. On all these maps, the position of site ODP 976 is indicated by a yellow circle.

Fig. 2. (**a**) Différence (LGM–H1) en température du mois le plus froid, simulée par le modèle ; (**b**) différence en précipitation annuelle (H1–LGM), normalisée par la valeur de LGM, en % ; (**c**)–(**f**) fractions couvertes d'herbes et d'arbres, simulées pour les expériences LGM et H1 : (**c**) fraction d'herbes pour le LGM, (**d**) fraction d'arbres pour le LGM, (**e**) fraction d'herbes pour H1, (**f**) fraction d'arbres pour H1. Sur toutes ces cartes, la position du site ODP 976 est indiquée par un cercle jaune.

4.3. Vegetation

The vegetation simulated by the ORCHIDEE model forced by the LGM and H1 climates produced by the atmospheric general circulation model LMDZ.3.3 are shown on Fig. 2c–f. These two simulated vegetations mainly consist of grasses (compare (c) to (d) and (e) to (f)), with a few trees. The difference between the LGM and H1 grass fractions around the Alboran Sea is not very large, consistent with the fact that in the pollen record, the semi-desert taxa increase during H1 compensates the decrease in herbaceous categories (Fig. 1). The model simulates a decrease in tree fraction during H1, compared to LGM, which is consistent with the pollen record. However, the specific tree types found in the pollen record, which are altitudinal species, are not exactly represented in the model Plant Functional Types. Furthermore, the Ericaceae group is difficult to attribute to a model Plant Functional Type, which prevents a complete comparison between the two periods. Indeed, it is this group, together with herbaceous plants and *Cedrus*, whose association defines best the Last Glacial Maximum.

5. Conclusions and perspectives

This study presents palynological reconstructions from the Alboran Sea for the period between 21.5 and 14 ky BP, which includes Heinrich Event 1 and the Last Glacial Maximum. The vegetation and climate in this region of the western Mediterranean Sea are deeply affected by H1: the temperature of the coldest month decreases by 5 to 15 °C, while the climate becomes very dry. Semi-desert taxa increase at the expense of other grasses and Ericaceae and altitudinal forests decrease. This record gives a good example of how variations in the states of the ocean, climate and vegetation are correlated since all changes are deduced from the same core. When such information is collected for the LGM and H1 periods, it would constitute a very good test for climate and vegetation models to assess their capability to simulate abrupt changes related to variations in the state of the thermohaline circulation.

Using a vegetation model forced by an atmospheric general circulation model, we have investigated the response of the glacial climate to a 4 °C anomaly in North Atlantic sea surface temperatures. The response in climate is significant on the European Atlantic coast but decreases very rapidly inland, making the model response hardly comparable to climatic reconstructions in terms of the temperature of the coldest month and not large enough in terms of precipitation. The vegetation response to this climatic change compares rather well to data but the comparison can be difficult when different taxa are grouped within one category in the model. However, these experiments show that the glacial vegetation is very near climatic thresholds and that a minor change in temperature and a reduction in the hydrological cycle result in significantly different vegetation distributions.

The work presented here is preliminary. In the following we list several improvements that can be easily envisaged, for the pollen-inferred climatic reconstructions as well as for the models:

(1) To refine the climatic reconstructions based on pollen data, we need to complete the modern database with additional spectra especially in region where the LGM taxa are well represented in order to have better modern analogues for the LGM pollen spectra. In a second step, we may constrain the method by a biome selection (Guiot et al. [11]). We can also apply the Plant Functional Type method [24] which is efficient in no analogue situations.
(2) The sea surface temperature anomalies used to force the atmospheric model need to be more realistic. For the North Atlantic, new reconstructions could be based on the reconstructions presented in this volume [9]. It is also essential to impose available Mediterranean reconstructions for H1. This would certainly lead to a larger impact on the climate and vegetation around the Alboran Sea. Including the vegetation feedback into the atmospheric simulation design is also an important point, which we could address by using the vegetation obtained in the present work as the first step of the feedback.
(3) For a more adequate comparison between the vegetation model results and pollen diagram, a distinction between semi-desert taxa and other herbaceous within the vegetation model would be useful.

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