H4 abrupt event and late Neanderthal presence in Iberia

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Abstract

Heinrich event 4 (H4) is well documented in the North Atlantic Ocean and the adjacent continents as a cooling event 39,000 yr before present (BP). To quantify the impact of this event with respect to climate and vegetation over the Iberian Peninsula, we perform numerical experiments using a high-resolution general circulation model forced by sea surface temperatures before and during H4. Our model simulates an expansion of aridity over the peninsula during H4, a desertification of the south, and a replacement of arboreal by herbaceous plants in the north, all of which are in agreement with contemporaneous pollen sequences from marine cores located off the Iberian Peninsula. Our simulations demonstrate that the H4 marine event imprinted drastic changes over Southern Iberia, which would not have favoured its occupation by Anatomically Modern Humans, therefore providing a plausible explanation for the delayed extinction of Neanderthals in this region inferred from the archaeological record.

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1. Introduction

The dynamics of the colonisation of Europe by Anatomically Modern Humans (AMH) and Neanderthal extinction are the subjects of lively debate [1–6]. Climatic variability has been repeatedly invoked as a potential cause for such crucial population events [2], occurring at ca. 41–32 cal ky BP (37–29 14C ky BP) [7].

Several hypotheses based on ecological factors have been put forward to explain the apparent late survival of Neanderthal populations in the southern and western regions of the Iberian Peninsula. The first of these hypotheses suggests that AMH populations bearing an Aurignacian technology may not have expanded south of the Ebro River during Interstadial 9 which occurred just prior to Heinrich Event 4 [8–10] (H4, 39,000 calendar yr BP) [11]. This lack of expansion to the south may have been due to the fact that the regions to the south were significantly more wooded [12] and thus less...
favourable since large mammals, on which their subsistence systems were focused, preferred open landscapes. According to this hypothesis, AMH populations would have moved southwards only when the cold conditions associated with H4 allowed for the southern expansion of the prey species that formed the basis of their subsistence systems. Other authors [13] have proposed that the climatic changes of the Oxygen Isotope Stage 3 (OIS 3, between ca. 60 and 25 ky BP) could have fatally perturbed the Neanderthal seasonal activity cycle even before the arrival of modern competitors in these southern regions. A third scenario [2], based on comparisons of archaeological and pollen data, suggests that the late survival of Neanderthals in Southern Iberia is the consequence of the expansion of semi-desert environments over this region due to the climatic conditions associated with H4, which limited the advance of AMH groups, dependent on large ungulate species, into regions south of the Ebro. Such a scenario would have delayed the replacement and eventual extinction of Neanderthals. The aim of this paper is to use appropriate models to evaluate these hypotheses in terms of climatic and vegetation changes associated with H4.

The small number of human remains associated with archaeological material dated to this period represents a major problem for testing hypotheses regarding the nature, extent, and chronology of relationships between AMH and Neanderthals. It is generally acknowledged, however, that the Aurignacian culture is a reliable proxy for the dispersal of AMH, that these new populations arrived in regions north to the Iberian Peninsula between 42 and 41 ky cal BP (37–36 14C kyr BP [6,7], and that their colonisation of southwestern Iberia occurred much later, at around 35,200 cal BP (33 14C kyr BP) [14]. We argue that the impact of H4, which is centered around ca. 39 ky BP, and its imprint on vegetation for a period of more than 1000 yr, played an important role in this process. This phenomenon may explain, in part, the delay in Modern Humans progression southward and the longer survival of Neanderthal populations in the south of Iberia.

Data from deep-sea sediments [8], continental sequences [15] and polar ice cores [9] show that, during OIS 3, several abrupt climatic shifts occurred over the Atlantic Ocean and Europe. High levels of lithic icerafted debris (IRD) and low foraminiferal concentrations define several Heinrich events of massive iceberg discharges in the North Atlantic Ocean [10,16,17]. Among them, H4 was associated with strong decreases in North Atlantic Sea Surface Temperatures (SSTs) [18]. Its exact date is still a matter of debate (e.g. see Bard et al. [11] and Shackleton et al. [19]) but Roche et al. [20] suggest 38.9 and 39.3 ky BP as the most plausible dates. The duration of the meltwater injection in the North Atlantic corresponding to this event has been recently updated to 250±150 yr [20]. The duration of the cooling due to this perturbation is longer, as the thermohaline circulation needs another 400 yr to adjust and restart after the end of the meltwater pulse. In terms of continental response, considering these ranges and regarding vegetation dynamics, it seems that the H4 could have perturbed the biosphere for at least one millennium (see discussion). Previous modelling studies [3] have been conducted on the OIS 3 palaeoclimatic [21] and palaeovegetation [22] variations, but have not specifically focused on the impact of an abrupt cold climatic shift on neighbouring continental areas. Kageyama et al. [23] investigated the impact of H1 over western Europe in terms of temperature and water cycle, but the interest of H4 is that this climate shift may have occurred contemporaneously with important changes in human populations. Yet no spatial reconstruction of the H4 impact on Iberian vegetation is available. Well-dated indications of environmental changes are recorded in pollen-rich marine cores located off the Iberian peninsula [24,25] and allow for comparisons with our model outputs. Here we present two simulations made with a Global Circulation Model (GCM) quantifying the climatic and vegetation response before (BH4) and during (DH4) Heinrich 4 event.

2. Methods

To quantify climate changes produced by H4 over this region, we use the atmospheric general circulation model (AGCM) called LMDz developed at Laboratoire de Météorologie Dynamique [26] with a high regional resolution over western Europe, providing a 60 km resolution over Iberia. The Dynamic Global Vegetation Model (DGVM) ORCHIDEE [27] is forced by climate variables produced by LMDz in order to quantify the spatial distribution of vegetation changes on the Iberian peninsula. In order to evaluate the environmental impact of the H4 event over Iberia, we run two numerical experiments with the AGCM. The first experiment (BH4 for “Before H4”) aims at estimating the climate just before H4. It is constrained with appropriate 39 ky cal BP orbital parameters [28] and CO2 concentration set at 209 ppmv (partial pressure in parts per million, from the Vostok ice core [29]). Since no global dataset describing the SSTs before the H4 exists, the SSTs used for this first simulation are those given by the CLIMAP [30] Last Glacial Maximum global reconstructions. Similarly, no global ice-sheet reconstruction is available for this period, but the sea-level drop at that time is
estimated to be 60 m lower than present [31]. We have therefore chosen to use the 14 ky BP ice-sheets reconstruction from Peltier [32] (ICE4G) which corresponds to the same sea-level drop, and which is the closest reconstruction to the ice sheets which existed before and during H4. This reconstruction is consistent to what other authors used for the same period [33]. Thus our first experiment is a “glacial” state, with appropriate boundary conditions representing the pre-H4 conditions.

In the second experiment (DH4 for “During H4”) we keep the same boundary conditions (insolation and CO2 concentration vary very little between before and after H4) except for the SSTs. We cool the North Atlantic using H4 SST anomalies consistent with reconstructions by Cortijo et al. based on the modern analogue technique applied to planktonic foraminifera assemblages [18]. These authors reconstruct SSTs at several points in the North Atlantic Ocean. Error bars associated with these reconstructions are rather weak compared to the anomaly. We use these reconstructions to create zonal temperature anomalies that we apply to the CLIMAP SST dataset (Fig. 1). LGM SSTs are reduced by 4 °C between 40°N and 50°N, 3 °C between 50 and 54°N, 2 °C between 54 and 60°N, and 1 °C towards the North Pole. Southward from 40°N, the imposed anomaly follows a linear decrease to reach 0 °C at 32°N. Sea ice is imposed where SST is lower than −1.8 °C. By applying these anomalies to CLIMAP SSTs, we simulate the cooling effect of the H4 over the North Atlantic. Reconstructions from Gulf of Cadiz [34] and off western

![Fig. 1. SST anomalies (grey scale bands) applied to the CLIMAP dataset for the DH4 experiment. Between 40°N and 60°N, top and bottom numbers indicate absolute values of summer SSTs as reconstructed from Cortijo et al. [18] and prescribed in the DH4 run, respectively. Top and bottom numbers below 40°N indicate mean SSTs reconstructed from [34,35] and prescribed in the DH4 run, respectively.](image-url)
Africa [35] also suggest a cooling at lower latitude during H4. However, CLIMAP SSTs are consistent with the reconstructed values for H4 at these latitudes (Fig. 1), so we did not add a supplementary negative anomaly. Further modelling studies may have to assess the potential impact of such low-latitudes anomalies to see if it can affect atmospheric circulation and precipitation patterns over Iberia. Both experiments have been run for 11 yr and provided outputs that have been averaged over the last 10 yr to define the BH4 and DH4 climates.

The vegetation response to these climatic changes is computed with the ORCHIDEE model in stand-alone mode, i.e. forced by outputs from the climate simulation. ORCHIDEE is forced by diurnal cycle variation, daily rainfall, monthly means of air temperature, relative humidity, 10-meter wind speed and cloud cover, all these variables coming from daily outputs of the two climatic experiments. To be consistent with the CLIMAP SSTs used for the BH4 experiment, the initial vegetation cover comes from the equilibrium results of ORCHIDEE forced by the climatic outputs of a classical run of the Last Glacial Maximum (LGM) [36]. This glacial vegetation was used as initial condition for our two simulations that were run for 200 yr to reach equilibrium. Additional climate simulations, forced by the resulting vegetation, have also been performed to check that the vegetation feedback does not have a strong impact on the regional climate. The equilibrium vegetation is described in terms of Plant Functional Types (PFTs) [37]. We compare our results to pollen data from four deep-sea cores taken off the Iberian margin. High-resolution pollen records from IMAGES MD95-2042 and MD95-2039 cores reflect vegetation changes that occurred during OIS 3 in western Iberia, whereas those from MD95-2043 and Ocean Drilling Program 976 (ODP 976), retrieved in the Alboran Sea, cover the floristic changes that took place in western Mediterranean borderlands [24,25]. These cores contain unambiguous signatures of H4, in terms of percentage of polar foraminifera as well as variations of the pollen assemblages.

The archaeological data used in this study were compiled from a variety of sources by two of us (FdE and MV) in the framework of a project funded by the ECLIPSE program of the Centre National de la Recherche Scientifique. This database contains the geographic coordinates, recorded stratigraphic levels, associated cultural affiliations, and ca. 6000 radiocarbon ages from ca. 1300 archaeological sites in Europe. In an effort to minimize the possibility of incorporating sites associated with radiocarbon ages that are underestimates of their true ages, we only considered sites with AMS ages, and conventional

3. Results

The annual rainfall over the Iberian Peninsula follows a NW-SE gradient for both simulations (Fig. 2a, b). Rainfall occurs primarily from November to March and is related to winter storms, with the strongest storms along the Iberian NW coast. The BH4 experiment shows high rainfall (>800 mm/yr) over Northwestern Iberia, while the southeast is very dry (<100 mm/yr, Fig. 2a). This pattern changes in DH4, with the decreased SSTs leading to an extension of arid zones from the south to the center-west of Iberia (the 200 mm isohyet moves northwestwards), and the reduction of the northwestern precipitation. On the Atlantic coast, the 200 mm isohyet shifts northward by 2°. This change is not associated with a reduction in storminess. Rather, the storms coming from the Atlantic carry colder and therefore drier air towards the Iberian region. On the other hand, the cooling over the North Atlantic produces a relatively weak decrease of continental annual temperatures (0.5 to 1.5 °C), which mainly occurs on the Atlantic coast (Fig. 2c, d).

Precipitation estimates [24,25] inferred by applying to the pollen record the modern analogue technique [39,40] indicate a precipitation decrease by 400 mm on the Atlantic and by 500 mm on the Mediterranean side during H4. Our simulations are consistent with this decrease on the Atlantic coast (Fig. 2b). However, some discrepancies exist on the Mediterranean side, which is already very dry in our BH4 experiment (<50 mm/yr) and prevents the model from simulating an anomaly as large as 500 mm/yr. However the essential result is that the DH4 experiment reproduces the rainfall gradient occurring during the event between the two sides of Iberia satisfactorily.

The cooling and drying of H4 induce large vegetation changes. The maximum vegetation fraction (i.e. the maximum value of total vegetation cover over a pixel) is already very low in BH4 (<50%, Fig. 3a). This fraction shifts to even lower values (<25%) in DH4, with a northward expansion of desert-like environments, especially
north of the Ebro valley (Fig. 3b). Simultaneously, the already weak arboreal percentage (<10%) decreases in inland Iberia, but remains constantly close to the southwestern coast, with a mean fraction of 15% (Fig. 4a, b). The model simulates significant changes in the three woody PFTs present in Iberia. Boreal and Temperate Broadleaved Summergreen trees occupying the center of the peninsula and southwest Portugal in BH4 undergo a strong reduction during H4. Temperate Needleleaf trees, initially present over a large part of the peninsula, are
essentially confined to the Atlantic coast during this cold event. Grasses remain on the Cantabrian and Mediterranean coasts as well as in the Ebro basin (Fig. 4c, d). Pollen data [24,25,41,42], which show abrupt decrease in open Mediterranean forest (deciduous and evergreen Quercus, Phillyrea, Olea, Pistacia, associated with Ericaceae) and

Fig. 3. Maximum percentage of vegetation cover simulated over Iberia and geographic distribution of radiocarbon dated Mousterian and Aurignacian sites before (a) and during (b) the Heinrich 4 event. (c) Geographic distribution of radiocarbon dated Mousterian and Aurignacian sites after the Heinrich 4 event.
increase in steppe-to-semi-desert vegetation (*Artemisia*, Chenopodiaceae, *Ephedra*) are in good agreement with our model outputs. In the North, H4 triggers a reduction in deciduous woodland and pine forest, and an expansion of grassland. The MD95-2042 core (Fig. 5) gives important information concerning the timing of the vegetation response to H4. It shows that the maximum of semi-desert plants occurs ca. 1000 yr after the $\delta^{18}O$ perturbation and the first Ice Rafted Debris peak. Moreover, high percentages of semi-desert plants last longer than the IRD/$\delta^{18}O$ event, and another millennium is necessary for the vegetation to recover from H4. Thus there is a clear delay between the maximum ocean perturbation and the onset of aridity over the continent.

The geographic distribution of archaeological sites before H4 (Fig. 2) identifies numerous Mousterian and Aurignacian occupations in Northern Iberia and a few Mousterian coastal sites in the South. During H4, the Aurignacian remains confined to the North and the number of sites decreases in Northern Iberia. Two sites, Foradada and Beneito, have $^{14}C$ ages that attribute their occupation to the H4 event. However, the cultural attribution of the layers that have yielded the dated samples is problematic. After H4, Aurignacian sites are
recorded in the North and the South of the Iberian peninsula while Mousterian sites only persist in the southwest and in the center.

4. Discussion and conclusions

The timing of Neanderthal extinction is a controversial issue [1–6,43–45]. However, previous research [2,4,46,47] and results presented here support the scenario of a late survival of Mousterian Neanderthals in Southern Iberia. The archaeological and radiocarbon evidence indicates that populations bearing Aurignacian technologies were already present in Northern Iberia at the onset of H4 but colonised the South only after this climatic event. The large aridification of Central and Southern Iberia depicted in our DH4 simulation implies a decline of land biomass (as simulated by our DGVM) the duration of which, as attested by the pollen record, could have led to a drop in the biomass of ungulates and consequent drop in Neanderthal population density. Development of semi-desert landscape in Iberian inland may also have resulted in delaying the Aurignacian advance. According to these hypotheses, competition between the two populations would have been temporarily prevented as environmental changes created a Southern refugium for Mousterian Neanderthals, which delayed their replacement by Aurignacian groups.

This study is based on a comprehensive simulation of the climate and continental responses, in terms of vegetation changes, to Heinrich event 4, using the most appropriate boundary conditions available. Our model results are in good agreement with pollen from marine
cores and challenge the hypothesis that a stationary Mediterranean forest persisted almost unchanged in Southern Iberia coastal areas during OIS 3 and was not affected by D-O millennial scale climatic variability [1,13,48–50]. The added value from the modelling approach is the spatialisation of the climate and vegetation response over Iberia. While modelling quantifies climate and vegetation responses spatially, paleoclimatic data provide relevant information concerning the timing and the duration of the latter’s response to the cooling. These results may underscore the role played by sub-millennial scale climatic variability on population dynamics during the Middle and the Upper Palaeolithic. Further studies will surely benefit from more and more accurate data, notably Sea Surface Temperatures reconstructions. Future modelling studies will have to use these new data (from Gulf of Cadiz [34], off western Africa [35] but also from Mediterranean Sea) to better constrain boundary conditions for H4 as well as for the other abrupt climatic events of the last 30,000 yr.

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