High resolution palynological record off the Iberian margin: direct land–sea correlation for the Last Interglacial complex

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Abstract

We present high resolution pollen, dinocyst and isotopic data for the Last Interglacial complex from marine core MD952042 (southwestern margin of the Iberian Peninsula; 37°48’N; 10°10’W; 3148 m). Direct land–sea correlation from this core indicates that during this period, North Atlantic sea surface temperatures were in phase with Iberian climate. Our palynological analysis suggests a Younger Dryas-like event at the Marine Isotope Stage (MIS)-6/MIS-5 transition. The analysis also indicates that the Eemian spans from the lightest isotopic values of MIS-5e (ca. 126 ky BP) to the heavier isotopic values towards the MIS-5e/MIS-5d transition. Therefore, the Eemian is not entirely equivalent to MIS-5e. Pollen analysis identifies four climatic phases of low amplitude during the Eemian. A Mediterranean climate in southwestern Europe is gradually replaced by oceanic conditions. The middle of the Eemian is characterized by an increase in precipitation on the land and ocean, associated with a slight cooling. This seems to be the result of a displacement of the Polar Front as far south as southern Europe during this period. After the Eemian, three relatively short climatic phases on land (Méliey I, St. Germain Ia and Montaigu cold event) occurred contemporaneously with three shifts of sea surface temperatures. The Montaigu event, first identified in terrestrial pollen sequences, is, therefore, also recorded in core MD952042 on the basis of pollen, dinocyst and planktonic isotopic data. Our results also show that the warm periods of MIS-5 are not characterized by similar climatic conditions on land. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Climatic variability is a global phenomenon [1] which involves changes in the atmosphere, continents and oceans. This variability, its mechanisms and consequences, therefore, can only be discussed on the basis of comparisons between marine, ice and terrestrial climatic data. However, the absence of sufficient chronological control for land-based sequences prior to 35,000 yr makes it difficult to accomplish detailed correlation of climatic fluctuations reflected by the ice, oceanic and continental records. Pollen-rich marine cores such as the core that we will present here, provide an excellent opportunity to establish a direct correlation between European
climate and North Atlantic environments. In particular, studies of the Last Interglacial complex (MIS 5, 130–74 kyr) can be crucial for learning about the present interglacial, since the Eemian, generally considered as the equivalent of the Marine Isotope Substage (MIS) 5e, and the Holocene periods are both characterized by minimum ice volumes.

The climatic instability which characterized the Last Interglacial complex in the North Atlantic region is no longer a controversial subject. High-resolution ice, marine and terrestrial records indicate high-frequency climatic variability during this period [2–6]. Within the Eemian (MIS 5e, 130–113 ka), and excluding the problematic GRIP sequence [9], ocean and terrestrial high-resolution records from the North Atlantic region differ from each other in the number and/or the amplitude of the climatic changes. Isotopic and pollen records from mid-latitudes suggest a quite stable period [7–9] whereas records from high latitudes reflect more than one cold spell during the Eemian [10,11]. Two hypotheses have been put forward to explain the difficulty of identifying Eemian climatic changes in the mid-latitude area [11]: the insensitivity of most transfer functions for detecting interglacial fluctuations, or the damping of the high latitudes climatic oscillations at lower latitude. In contrast, other studies on cores from the subpolar North Atlantic suggest weak amplitude fluctuations (1–2°C) for the high latitudes during the Eemian [12]. Some authors have proposed that changes in thermohaline circulation may have been responsible for the apparent differences in climatic variability during the Eemian [7,13].

In this study we address the following questions: What kind of climatic changes, if any, characterized the Eemian in the oceanic and European mid-latitudes? What were the mechanisms promoting this variability? Were the variations in the sea-surface conditions and European climate synchronous? Does the Eemian correlate exactly with MIS 5e? To answer these questions we will present high-resolution pollen, dinocyst and isotope records from IMAGES core MD952042 (37°48′N; 10°10′W; 3148 m water depth) and of the closest European cores mentioned in the text. Arrows indicate the direction of the dominant winds on the Iberian Peninsula. The distribution of the modern vegetation follows Walter (1954) in Blanco Castro et al. [15].

2. Environmental setting

2.1. Present-day vegetation and climate

The Tajo basin (at the center of the Iberian Peninsula) is characterized by a Mediterranean climate, mild winters (m: 5–1°C; M:13–8°C) and hot and dry summers (P_{ann} < 600 mm), with an important oceanic component in its western zone which gradually decreases eastwards [14].

The center of the Iberian Peninsula belongs to the biogeographical Mediterranean region but includes transitional zones, with Atlantic and Mediterranean floristic elements [15] (Fig. 1). The major part of this area, located below 1000 m a.s.l., is dominated by evergreen sclerophyllous forests. The western part is characterized by Quercus rotundifolia and Q. suber forests associated with among others Phillyrea angustifolia and Pistacia terebinthus.
In the warmest zones, thermophilous elements such as *Pistacia lentiscus* and *Olea sylvestris* form the forests. *Quercus rotundifolia* and *Q. coccifera* woodlands dominate the eastern part of this region, in which *Juniperus communis* and *Pinus halepensis* are also characteristic elements. The middle elevations (700–1000 m a.s.l., $P_{\text{ann}}>600$ mm) are occupied by deciduous *Quercus* forest (*Q. pyrenaica* and *Q. faginea*) associated with Eurosiberian species such as *Taxus baccata*. The degradation of this forest produces two types of matorral communities: rockrose shrublands (Cistaceae) in zones with precipitation between 600 and 1000 mm, and heath communities (Ericaceae) in wetter zones. The highest elevations (1000–2000 m a.s.l.; $T_{\text{ann}}:13-4^\circ\text{C}$, $P_{\text{ann}}>600$ mm) are colonized by coniferous forests and shrubland. Areas characterized by very cold and long winters and, particularly, dry summer conditions, are dominated by *Juniperus–Pinus* forest.

### 2.2. Sea surface conditions

Core MD952042 is located off the south west coast of Portugal, on the pathway of the Canary Current (Fig. 1). At present, this area is marked by a seasonal coastal upwelling (from July to September) due to an increase in the intensity and steadiness of northerly winds (Trade Portuguese Winds) during summer, in connection with the dynamics of the Azores anticyclone and with the Subtropical Front [16].

### 3. Material and methods

Core MD 952042 was collected with a Calypso corer [17]; it is 39.56 m in length and composed of hemipelagic clay. This core is continuous without corebreaks.

#### 3.1. Isotopic analyses

Isotope stratigraphy ($\delta^{18}O$) has been established so far on planktonic foraminifers [18]. About twenty specimens of *Globigerina bulloides* were picked by Olivia Cayre from the 250–350 micron fraction. The specimens were soaked in 10% hydrogen peroxide for 30 minutes and then broken and cleaned ultra-sonically in clean acetone. The measurements were made in Cambridge on a VG Isogas SIRA triple collector mass spectrometer using an automatic common acid bath preparation line. Values are calibrated to VPDB using the NBS19 standard; overall analytical precision is better than 0.1 per mil.

#### 3.2. Micropaleontological analyses

The core was sampled for pollen and dinocysts at 10 cm intervals and between 4 and 1 cm in the most interesting sections (key periods). An exotic, *Eucalyptus* or *Lycopodium*, spike of known concentration was added to each sample. The preparation technique followed de Vernal et al. [19]. After chemical treatment (cold 10%, 25% and 50% HCl, cold 48% and 70% HF), the samples were sieved through 10 mm nylon mesh screens. Acetolysis was not used, to avoid destruction of peridiacean cysts [20]. The final residue for pollen analysis was mounted unstained in bidistilled glycerine. For dinocysts, the residue was stained with fuchsine and mounted in glycerine jelly. Pollen and dinocysts were counted using a Zeiss Axioskope light microscope at $400$ and $1000$ (oil immersion) magnifications.

A minimum of 100 pollen grains, excluding *Pinus* and spores, and 20 taxa were counted at each of the 107 levels analysed. *Pinus* was excluded due to its over-representation in marine deposits [21]. The pollen percentages for terrestrial taxa are based on a main pollen sum which excludes *Pinus*, spores, indeterminables and unknowns. *Pinus* percentages are calculated based on the main sum, plus *Pinus*. Percentages of *Isoetes* have been made based on the total sum (Pollen + spores + indeterminables + unknowns).

An average of 300 dinocysts were identified and examined from each sample. The identification of dinocysts are based on Turon [21] and de Vernal et al. [22]. The *Brigantedinium* species were grouped together because of uncertainties in determination due to the orientation of the cysts. Additional counts were made on the same samples for foraminiferal linings and fresh water microalgae (*Pe- driastrum* sp. and *Concentricystes* sp.), and also on reworked dinocysts.
Fig. 2. Pollen percentage diagram with selected taxa together with the planktonic isotopic curve from core MD952042. *Chenopodiaceae* is used to indicate *Chenopodiaceae–Amaranthaceae* pollen type. In the lower part of the diagram, a pollen hiatus is visible due to low pollen concentrations. No difference in the percentages is, however, observed below and above this hiatus, suggesting that no vegetation changes took place at that time. The direct correlation between the terrestrial and marine stratigraphies is indicated in the center of the figure. Except for the term "Last Interglacial complex", continental stratigraphy follows Woillard's nomenclature [3]. We use the term *Last Interglacial complex* to refer to the succession of four warm periods (Eemian, St. Germain Ia, St. Germain Ic and St. Germain II) between the Linexert and Lanterné glaciations. The short horizontal lines on the $\delta^{18}O$ isotope curve represent marine isotope stage boundaries.
4. Results

4.1. Isotopic stratigraphy

Isotopic measurements identify the end of MIS 6 (133–129 ky), MIS 5 (129–74 ky) and the beginning of MIS 4. Within stage 5, the five sub-stages 5e to 5a are also identified [18] (Fig. 2). Their limits, however, cannot be clearly established because there is no formal definition of the substage boundaries within stage 5. Furthermore, the lack of the benthic isotope record makes it specially difficult to identify the 5e/5d boundary. Cayre assigns ages by correlation of this interval with the SPECMAP stack [18].

The average sedimentation rate is 12 cm kyr$^{-1}$ so that the temporal resolution for pollen and dinocyst samples varies between 100 and 1000 years.

4.2. Vegetation and climate on the Iberian Peninsula during the last interglacial complex

Data on the distribution patterns of pollen in recent surface sediments from the ocean floor off Portugal are not available. However, studies of modern pollen rain in marine samples from the Bay of Biscay [21] and the Mediterranean sea [23] indicate that the pollen spectra provide an accurate image of the integrated vegetation of the near continent. Moreover, we can assume on the basis of experimental studies in marine sediments [24] that the pollen preserved in the sediments of core MD952042 was mainly transported by the Tajo river. This assumption is particularly reliable for the sediments of the Tajo abyssal plain, where the dominant winds come from the northwest Atlantic. The vegetation which supplied pollen mainly came from the Tajo basin and, therefore, from a transitional zone composed by Mediterranean and Atlantic floristic elements (Fig. 1).

Pollen analysis identified 82 taxa (Fig. 2). Pollen richness (Fig. 3) oscillates between 898 and 21,722 grains per cm³. Maximum values correspond to cold periods and minima to warm periods. Fifteen pollen zones have been identified based on the definition by Birks and Birks [25] and, thus were defined independently of the marine isotopic stratigraphy. We interpret Artemisia, Chenopodiaceae and Ephedra as indicators of cold and dry climate since studies of the modern land pollen spectra from Eurasia and northern Africa indicate that pollen assemblages dominated by these taxa are characteristic of steppe environments [26]. In Iberia, the genus Juniperus includes warm and cold species and its pollen, indistinguishable from that of Cupressus, is placed into the Cupressaceae taxon. In our diagram this taxon shows high percentages during cool intervals suggesting the presence of cold species. We interpret them as indicating development of high elevation Juniperus-forest during these intervals. A prominent feature of the pollen diagram is the curve of Cedrus. This tree, nowadays absent from the Iberian vegetation, colonizes cool and moist environments between 1300 and 2600 m in the Rif, Middle Atlas and High Atlas mountains (northern Africa) [27]. The group of Eurosiberian plants, including temperate trees such as deciduous Quercus, Carpinus betulus and Corylus as well as the root-climber Hedera, indicate warm and wet conditions ($P_{ann} > 600$ mm). We interpret evergreen Quercus, Olea, Pistacia, Phillyrea and Cistus as indicators of Mediterranean climate. Today, in the center of Iberia, Ericaceae develop in zones with a level of precipitation above 1000 mm per year, which suggests that this group can be used as an indicator of an oceanic climate. The fern ally Isoetes mainly colonizes hydrophilous habitats [28]. The increase in the percentages of this taxon indicates a development of lacustrine environments and, therefore, an increase in rainfall.

Stratigraphical correlation (Figs. 2–4) has been established by comparison of our record with the western European long pollen sequences of La Grande Pile [3,29], Dèves (Lac de Bouchet + Ribains) [8], Les Echets [30], Padul [31] and Valle di Castiglione [32] as well as with the marine pollen records located off northwestern Africa [33] and in the Mediterranean sea [34]. The continental stratigraphic nomenclature follows the names used for La Grande Pile stratigraphical units [3].

Pollen percentage and concentration diagrams indicate an alternating development of Mediterranean/Eurosiberian forests and steppic vegetations, suggesting a succession of warm/cold phases during the Last Interglacial complex. From the bottom to the top of the sequence, three major types of plant communities can be distinguished.
4.2.1. Steppe communities

The episodes of steppe-like vegetation from which a dry and cold climate has been inferred can be correlated with the early stadial of the Linéxert glacial, the Mélisey I and II stadials and the Montaigu cold event. This steppe vegetation is characterized by *Artemisia*, grasses being very unimportant in Iberia, as in the other southern and middle European regions [26]. Some of these cold periods are associated with the expansion of the high elevation *Juniperus*-forest. The Mélisey I has the heaviest isotopic value of MIS-5d while the Montaigu event coincides with the second heaviest peak. The Montaigu event on the Iberian Peninsula is characterized, as in the northernmost European pollen sequences (La Grande Pile, Les Echets, Lac du Bouchet and Ribains) in which this event was identified for the first time, by a vegetation dominated by *Pinus*, and a re-expansion of steppe species [35]. The MD952042 pollen record also suggests the existence of pockets of deciduous and Mediterranean forest and the presence of *Abies* at this time. The cool and dry conditions during this period were not strong enough to eliminate these woodlands. The Mélisey II stadial, correlated with MIS-5b, is characterized by steppic elements along with high values of *Pinus* and *Cedrus*. It is generally assumed that *Cedrus* did not naturally grow in Iberia during the Last Climatic cycle. No *Cedrus* grains were found in either the analysis of the marine pollen record SU8132, located near the Spanish–Portuguese border (Turon, unpublished data), or in the first analysis of the Padul peat bog (south-eastern Spain) [36]. The new pollen analysis of this peat-bog sequence, covering the last 100,000 years, records isolated grains of *Cedrus* [31] which are interpreted as coming from northern
Africa. *Cedrus* pollen is recorded in Late Glacial sequences from the Iberian margin, associated with the appearance of African species, suggesting that *Cedrus* pollen was transported from Africa to the Iberian Peninsula [37]. The eastern part of the Tajo basin is influenced by the Saharan winds [14]. The high values of *Cedrus* in this part of the sequence might be the result of an intensification of these winds during this period and/or an increase of *Cedrus* populations due to a cooling and wetter climate in northwestern Africa.

Steppe–heathland vegetation is related to stadials I and II of the Lanterne glaciation [3]. Stadial I correlates with the heaviest isotopic values of MIS-5a while stadial II correlates with the beginning of MIS-4. Both suggest cold periods associated with wetter conditions, in contrast to the previous events.

### 4.2.2. Transitional vegetation community

A transitional period (MD42-2) is reflected at the beginning of MIS-5e. It is characterized by the persistence of the previous steppic landscape with Cupressaceae associated to the development of Ericaceae. The still high values of steppic pollen allow us to correlate this period with the end of the Linexert glacial period as is the case in the European pollen sequences [38,8]. At the same time, the arboreal taxa, mainly *Betula*, deciduous and evergreen *Quercus* developed, reflecting an increase in temperature and precipitation. At the end of this period, however, a stagnation of the arboreal development is detected (levels 2569, 2568, 2564 cm) along with a decrease in the Ericaceae. This may suggest a short cooling and drying phase that may be considered an analog of the Younger Dryas event. The previous samples would in turn be related to the interstadial before the Eemian (Zeifen interval).

### 4.2.3. Forest communities

Forest phases characterize the Eemian, St. Germain Ia, St. Germain Ic, St. Germain II and Ognon I. The maximum of *Olea* in zone MD42-3 is a characteristic feature of the beginning of the Eemian in the Mediterranean region [34,32] and in northwestern Africa [33] reflecting a Mediterranean climate. The rise in *Isoetes* values observed in this phase
may also confirm the correlation of MD42-3 with the first Eemian phase since the development of this fern ally is also observed at the beginning of the Holocene in the twin core SU8118 [39]. The following zone, MD42-4, records an increase in Ericaceae and, for the first time, pollen of *Carpinus betulus*. This zone suggests a change in the Mediterranean climate regime towards more oceanic weather associated with a decrease in winter temperatures. A decrease in winter temperatures during the *Carpinus betulus* phase has already been proposed for northwestern Europe [38,8]. In zone MD42-5, an initial maxima in Ericaceae together with an almost northwestern Europe [38,8]. In zone MD42-5, an initial maxima in Ericaceae together with an almost complete disappearance of Mediterranean taxa and a decrease in deciduous *Quercus* percentages suggests a short and slight cold event in the middle of the Eemian. The last Eemian phase suggests a warming and drying trend on the basis of a slight increase in Ericaceae. The Eemian is, therefore, subdivided in to four climatic phases and correlated with the lightest isotopic values of MIS-5e, and the heavier values towards the 5e/5d transition.

Because of its southwestern European position, the MD952042 pollen sequence shares Eurasian and Mediterranean botanical features (Fig. 4). For example, the development of *Carpinus betulus* in northwestern Europe during the Eemian is also reflected in our record. In contrast, in MD952042 the maximum forest development characterized by Mediterranean taxa is produced at the onset of the Eemian, whereas in the Eemian type section [38] and in the other northern European sequences [8,40] the highest values of *Quercetum mixtum* and *Corylus* are found in the middle of the Eemian. Taking into account that the insolation maximum took place during the very early Eemian, the late temperate tree colonization of northern Europe was probably due to the distance of these trees from their southern and eastern refugial zones. At the end of the Eemian, the *Picea-Abies* phase is not recorded in MD952042. *Picea* is absent from the diagram and *Abies* is sporadically present in transitional levels between cold and warm conditions, or vice versa, but always linked with isotopic values around 1‰. For the latest phase of the Eemian, northern European sequences would indicate, on the basis of an expansion of *Pinus* and *Picea* forests, a drop in temperature [38,41], whereas the MD952042 record suggests, in contrast, a slightly warmer and drier phase. The new study of the Hollerup sequence (Denmark) also reflects a cooling for the last phase of the Eemian associated with a possibly more arid climate [40]. A recent quantitative climatic reconstruction from seven European pollen records shows a discrepancy between La Grande Pile and the other records [42]. La Grande Pile reflects, as our record, a warming for the last phase of the Eemian.

St. Germain Ia is bracketed by two heavy isotopic peaks, the oldest one is included in the MIS-5d. It reflects a typical succession of vegetation from glacial to interglacial conditions similar to that observed at the Linexertl/Eemian transition. This succession is characterized by gradual colonization by pioneer trees (Cupressaceae, *Betula*, and *Pinus*) followed by the development of deciduous *Quercus*, *Corylus* and *Carpinus betulus* as well as the reappearance of Mediterranean elements. Therefore, the St. Germain Ia from core MD952042 records a major increase in temperatures and precipitations and can be considered as the beginning of an interglacial period (sensu Woillard) [3].

St. Germain Ic and St. Germain II temperate phases are characterized by the development of heathlands and deciduous and Mediterranean forests. They would correlate to MIS-5c and MIS-5a, respectively. The Ognon I period would correspond with an interstadial (sensu Woillard) [3] since it represents a relatively short and less-marked warming, which did not allow Mediterranean taxa to develop. It occurred at the end of MIS-5a.

4.3. Evolution of sea-surface conditions

Thirty four taxa of dinocysts were identified, with cell concentrations varying between 1000 and 17,000 cysts/cm³ (Fig. 5). The number of species per sample varies between eighteen and twenty nine. Dinocyst assemblages are alternately dominated by *Lingulodinium machaerophorum* and *Brigantodinium*, accompanied by *Bitectatodinium tepikiense* and *Impagidinium* species.

The end of MIS-6 and the beginning of MIS-5e (Termination II: 2650-2560 cm) is marked by two peaks of *B. tepikiense* and *N. labyrinthus*, associated
Fig. 5. Percentage curves of selected dinocyst taxa along with the concentration curves of *Concentricystes* sp., *Pediastrum* sp. and reworked dinocysts, and the planktonic isotopic curve from core MD952042. The short horizontal lines on the $\delta^{18}$O isotope curve represent marine isotope stage boundaries.

with maximum percentages of *Brigantedinium* spp. The present-day distribution of the two first species corresponds to a cold to temperate domain. Therefore, the *B. tepikiense* and *N. labyrinthus* peaks, associated with positive $\delta^{18}$O values, would indicate the penetration of cool North Atlantic waters and could be related to [5] a southward migration of the North Atlantic Polar Front. The last *B. tepikiense* peak, which marks the end of the 6/5e transition, could be associated with a distinct event, similar to the ‘Younger Dryas event’. The end of the MIS-6 is also characterized by an optimum in the dinocyst concentration and the high development of *N. labyrinthus*. This could reflect [43] a high marine productivity due to an intensification of the upwelling dynamic.

During the lightest isotopic values of MIS-5e (2560–2520 cm), a succession of warm species such as *Impagidinim patulum*, *I. striatum*, and *Spiniferites mirabilis* is recorded, along with a sharp decrease in the dinocyst concentrations (15,000–3000 cysts/cm$^3$). They reveal an improvement of the sea surface conditions and a decrease of the phytoplanktonic productivity.

The heavier isotopic values of the overlying section (2510–2470 cm) correspond with an abrupt increase of *L. machaerophorum* percentages to quasi-
monospecific values (70%). Two major hypotheses can be proposed for this increase: a period of high precipitation, producing a well stratified water column (de Vernal, per. com.) or an arrival of allochthonous material resulting from enhanced freshwater runoff. During this warm period of assumed high sea-level, the stability in the concentration values of Concentricystes sp., Pediastrum sp., reworked dinocyst and pollen shows, however, no evidence of an increase in the fluvial discharge (Figs. 3 and 5). Intense pluviosity on the ocean could have caused a higher stratification of the upper water column and, therefore, the high development of L. machaerophorum. This time interval is also characterized by a decrease in percentages of Impagidinium and a low diversity of warm species suggesting a slight cooling in sea-surface temperatures. After this cool event, dinocyst assemblages show a return to warm sea-surface conditions with the re-occurrence of warm dinocyst assemblages showing a return to warm sea-surface temperatures. After this cool event, dinocyst assemblages show a return to warm sea-surface conditions with the re-occurrence of warm species such as Spiniferites mirabilis and Impagidinium.

The two following heaviest isotopic values correlate with an increase in Brigantedinium spp. and B. tepikiense. As for the MIS-6/5 transition, peaks of B. tepikiense are associated with peaks of N. labyrinthus and with a dramatic decrease in the warm species. Between these peaks, relatively light values of δ18O coincide with an increase in warm dinocysts suggesting a short warming in surface waters.

In contrast to the MIS-5e, MIS-5c is marked by a uniform composition of the dinocyst assemblages. L. machaerophorum represents up to 70% of the investigated samples associated with the development of the warmer Impagidinium species and S. mirabilis. This particular assemblage seems to be close to the present day assemblage observed off the Portuguese margin (core SU 8118 Turon unpublished).

MIS-5b is characterized by a maximum occurrence of B. tepikiense together with an increase in δ18O values, indicating the re-occurrence of cold sea-surface temperatures during this period.

MIS-5a is marked by a clear tripartite climatic evolution. The base and the top correspond to high percentages of Impagidinium species, reflecting warm sea surface conditions, while the mid stage corresponds to the development of B. tepikiense and the virtual disappearance of thermophilous cysts.

5. Direct land–sea correlation

At the end of MIS-6, dry and cold conditions on the continent are contemporaneous with low sea-surface temperatures and a permanent upwelling regime (Fig. 6).

The MIS-6/5e transition is characterized by a general warming and an increase in precipitation on the continent, contemporaneous with a decrease in the arrival of cold water masses. This warming coincides with increasing values in mean annual and summer insolations [44]. However, this tendency to warm conditions stops at around 126 ky. Relatively high insolation during the year, and during the summer, could produce ice fragmentation and the arrival of cold water masses is reflected in the increase in cold dinocysts species, in particular B. tepikiense. In nearby areas of the continent this arrival of cold waters could produce the stagnation of Quercus forests associated with the re-expansion of steppics. This Younger Dryas-like event, just prior to the establishment of clear interglacial conditions, has already been reported at Termination II from northern latitudes cores [5,10,12,45,46].

Direct land–sea correlation in MD952042 shows that the Eemian corresponds to the lightest isotopic values of MIS-5e (ca. 126 ky BP) and the heavier values towards the 5e/5d transition. Therefore, the first phase of the Eemian does not coincide with the beginning of the MIS-5e. This contrasts with the recent works of Kukla et al. [47], Broecker [48] and Björck et al. [40] who propose, on the basis of an indirect land–sea correlation, that the Eemian corresponds to the entire MIS-5e and a substantial part of MIS-5d. In our record, the maximum development of the Mediterranean vegetation within MIS-5e represents the warmest phase of the Eemian and coincides with the optimum in sea surface temperatures as indicated by the development of tropical dinocysts. The following period reflects a higher level of precipitation and a cooling on the continent in comparison with the previous phase. High percentages of L. machaerophorum probably indicate an increase in precipitation over the ocean. Quantitative climatic reconstructions from terrestrial pollen data, foraminiferal and modelling studies also suggest a more cyclonic weather type for the second part of the Eemian in the Atlantic region.
This wet and cool period is linked with a gradual reduction of mean annual and summer insolations [44] and probably produced by a displacement of the Polar Front towards the south. A maximum cooling was maintained for over 400 years. This climatic event may perhaps be correlated with the cold isotopic event identified in the middle of the Eemian in the Norwegian Sea and North Atlantic Ocean [7,52] and with the K2 event of the northern seas [10]. In the Norwegian Sea and the Atlantic Ocean, this mid-Eemian cooling lasted, as in our core, for around 400 years [52]. Cortijo et al. [7] explain this short cooling as the result of a decrease in thermohaline circulation in the Norwegian Sea, enhancing the SST gradient between this water mass and the North Atlantic. This, in turn, favored the formation of major atmospheric depressions, bringing winter snow and promoting ice-growth over the continents. Our data indicate that the transition from a Mediterranean to oceanic climate in the North Atlantic mid-latitudes is linked with an enlargement of this cyclonic zone to southwestern Europe. The last Eemian phase witnessed the re-establishment of slightly warmer conditions both on the continent and the sea surface waters. From the Eemian optimum to the Mélisey I, four climatic phases on the continent can be distinguished and three shifts in the hydrological conditions. These climatic changes suggested by our pollen record are gradual, and of small amplitude, lasting between 2000 and 4000 years. These conclusions do not agree with those from the GRIP core and from the Lac du Bouchet pollen and magnetic susceptibility analyses, which would suggest abrupt climatic changes during the Eemian [53]. However, the GRIP Eemian signal has been questioned, and the trans-
fer functions applied to the Lac du Bouchet pollen record [8] may not reflect any significant climatic variability.

Pollen and dinocyst data suggest three relatively short climatic periods after the Eemian: the Mélisey I stadial, the first part of the St. Germain I warm period and the Montaigu cold event. The correlation of these climatic phases with the isotopic stratigraphy is problematic due to the lack of formal boundaries between substages. Consequently, the Mélisey I can be contemporaneous either with a part of MIS-5d or with the entire substage, while the St. Germain Ia and the Montaigu event can be included either in the MIS-5d or in the MIS-5c. A warm peak within MIS-5d is suggested by the maxima in wt% CaCO$_3$ and $\delta^{13}$C in the North Atlantic core GPC9 (Bahama Outer Ridge) [49] suggesting, as in our record, a strong warming following the Eemian. However, the latter authors note, on the basis of a subjective curve-matching correlation, that this warming is not evident in Grande Pile pollen sequences. Our direct pollen–isotopic correlation demonstrates that this warming corresponds to St. Germain Ia, clearly established in Grande Pile records.

The St. Germain Ic period is characterized by temperate oceanic conditions in the Iberian Peninsula. High pluviosity over the ocean and continent during this period indicates climatic conditions like those of the middle part of the Eemian.

During MIS-5b a new penetration of cold water masses is coeval with the cold and dry climate of Mélisey II in southwestern Europe. It has been suggested from pollen [54] and foraminiferal data [55] the enhancement of the northwestern African winds during MIS-5d and 5b. Our data could also suggest an intensification of southern winds during the Mélisey II stadial (MIS-5b), on the basis of the highest values of north African Cedrus in this period. $\delta^{18}$O values within MIS-5a reflect, as do dinocyst assemblages, three shifts in sea surface conditions. These shifts are contemporaneous with the three climatic phases detected from pollen data (St. Germain II, Stadial I, and Ognon I). St. Germain II, like the middle part of the Eemian and the St. Germain Ic, was characterized by a relatively high level of rainfall. During Stadial I, the expansion of steppics is associated with heathland formations indicating a relatively high level of precipitation contemporaneous with the arrival of cold water masses over the ocean. The climate on the near continent was not as dry as that of the previous cold periods. The slight re-expansion of the forest cover reflects the Ognon interstadial. Our direct land–sea correlation does not contradict the stratigraphical position of this interstadial inside the MIS-5a suggested by Woillard and Mook [56].

6. Conclusion

Direct land–sea correlation from core MD952042 demonstrates that during the Last Interglacial complex, the terrestrial climatic signal was similar to that of the ocean. North Atlantic sea-surface temperatures were in phase with European climate (at a resolution of between 100 and 1000 years).

High-resolution palynological results reveal a Younger Dryas-like event and, therefore, a two-step deglaciation at Termination II contemporaneous with the beginning of MIS-5e. They also reveal that the Eemian corresponds to the lightest isotopic values of MIS-5e and the heavier values towards the 5e/5d transition. Pollen and dinocyst data allow, furthermore, characterization of different climatic phases during the Eemian which are difficult to establish on the basis of the isotopic data alone. Mediterranean vegetation is gradually replaced by Eurosiberian formations indicating a change from Mediterranean to oceanic climates. In our record, the warming conditions of the Eemian are interrupted in the middle of this period by an increase in precipitation associated with a slight cooling. The contemporaneous decrease in mean annual and summer insolation could produce a cooling over the high latitudes and a reduction of the North Atlantic thermohaline circulation, promoting the southward displacement of the Polar Front and, therefore, major atmospheric depressions as far as southwestern Europe. A slight warming and drying trend characterizes the last phase of the Eemian. The low amplitude oscillations which characterize this climatic variability are not equivalent to the abrupt and high amplitude climatic changes indicated by the GRIP record.

Following the St. Germain Ia warm period, the Montaigu cold event, first identified in continental pollen sequences, is also detected in our marine
record on the basis of pollen, dinocysts and planktonic isotopic data.

Palynological data also show that warm periods of MIS 5 are not characterized by similar climatic conditions. Our climatic reconstruction suggests that the middle part of the Eemian and the St. Germain Ic (MIS-5c) and II (MIS-5a) temperate periods were strongly marked by the oceanic perturbations, in contrast with the Mediterranean climate of the early part of the Eemian. This conclusion does not agree with that from the quantitative climatic reconstruction of French pollen sequences which suggest that [8] the temperate episodes of St-Germain I and St-Germain II were more continental, contrasting with the oceanic character of the Eemian.

The MD952042 record reflects four intervals in which cold water masses arrived during MIS-5, corresponding to MIS-5d, the Montaigu event, MIS-5b and stadial I of the Lanterne Glaciation. These periods can be correlated with the four Heinrich-equivalent events detected in core DSDP609 (49° 53′N) [5]. Therefore, it appears that polar water advances during MIS-5, detected at around 50°N in the northeastern Atlantic, also affected the southern mid-latitudes. During these periods, southwestern Europe was colonized by a steppe-like vegetation, the result of a dry and cold climate.

For the Last Interglacial complex (MIS-5), our results indicate that strong climatic and hydrological changes previously described in high-latitude records of the North Atlantic region are also found in mid-latitude records.

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