Oceanic *versus* continental influences over the last 7 kyrs from a mid-shelf record in the northern Bay of Biscay (NE Atlantic)

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Abstract :

We discuss paleoenvironments of north-western France over the last 7 kyrs in terms of: i) long-term changes (relative sea-level rise and boreal summer insolation), ii) rapid climate changes (millennial-scale Bond events and multi-decadal regimes of the North Atlantic Oscillation: NAO) and iii) growing human impacts in watersheds. Our study focuses on the CBT-CS11 core, retrieved in the northern Bay of Biscay, with new high-resolution (70 years) palynological data (dinoflagellate cysts and pollen), combined with sedimentological and oxygen stable isotopic records. This multiproxy approach enabled us to gain a better understanding of the influence of varying Middle to Late Holocene climate regimes on marine, coastal and terrestrial ecosystems as well as on human coastal societies. We especially show that the slowdown of the relative sea-level rise, starting at around 5.9 ka BP, led to the stabilization of tidal flats in estuarine environments. Subsequently, increasing river flows to the ocean resulted in a progressive seasonal stratification of the shelf under increasing winter precipitations and establishment of the modern winter thermohaline front at 3.3 ka BP. In addition, within the 4–2 ka BP interval, palynological and sedimentological evidence suggests increasing river discharges in north-western France, in a context of

a weakened Atlantic subpolar gyre and recurrent negative "NAO-like" conditions. Finally, we identified a major transition at around 1.2 ka BP (Early Middle-Ages) that appears to be linked to a period of maximal anthropogenic landscape opening and soil erosion, implying stronger primary productivity in coastal surface waters of the studied region.

Highlights

► Paleoenvironments of north-western France over the last 7 kyrs (northern Bay of Biscay). ► New high-resolution (70 years) palynological data combined with sedimentological and stable isotopic records. ► The slowdown of the sea-level rise has led to the stabilization of tidal flats in estuarine environments at 5.9 ka BP. ► The modern winter thermohaline front established on the Armorican shelf at 3.3 ka BP. ► River discharges increased during the 4–2 ka BP interval (weakened subpolar gyre, negative "NAO-like" conditions). ► Maximal landscape opening, soil erosion, and coastal productivity increase, occurred at 1.2 ka BP (Early Middle-Ages).

Keywords : Holocene, Vegetation dynamics, Stable isotopes, Atlantic subpolar gyre, Rapid climate changes, Precipitation regimes, Winter horizontal thermohaline front

1. Introduction

Paleoenvironmental studies of the Holocene (i.e., the last 11.7 kyrs) raise questions about environmental changes under mixed natural and anthropogenic forcings. However, in marine sediment archives, it is difficult to discriminate signals induced by natural modes of climate variability, integrating the complexity of atmosphere-ocean-biosphere-cryosphere-lithosphere interactions, from those produced by anthropogenic activities and their impacts on the surrounding watersheds. Studying Holocene sediment archives often requires interdisciplinary studies (e.g., combining geology, geography, geochemistry, paleoecology, archaeology) to unambiguously disentangle natural and human signatures of environmental changes recorded in sediments.

Over the long-term decrease in summer insolation at boreal latitudes that started around 9 kyrs ago (Berger and Loutre, 1991), high-resolution Holocene studies mainly addressed the question of millennial time scale climate shifts (abrupt cooling events in the North Atlantic: Bond et al., 1997, 2001, also referred to as Rapid Climate Changes with a more global-scale perspective including cool poles and dry tropics: e.g., Mayewski et al., 2004). Previous studies suggested the existence of solar-induced cycles of 2,500 years throughout the Holocene (e.g., Debret et al., 2009). Superimposed on the latter, a 1,500-year (e.g., Bond et al., 1997, 2001; Debret et al., 2007, 2009; Wanner et al., 2008; Thornalley et al., 2009; Sorrel et al., 2012) or 1,250-year (Mojtahid et al., 2019) mode of periodicity was identified as having existed over the Middle to Late Holocene and attributed to internal forcings. Uncertainties nonetheless subsist concerning the main drivers of these latter modes and their different impacts according to the investigated area (e.g., Mayewski et al., 2004; Eynaud et al., 2018).

Another concern is the impact of human activities on landscapes (deforestation and land use for cultures, pastoralism, living areas and access to terrestrial and/or marine resources; Ruddiman et al., 2016) and, by extension, on near-continent sea-surface water characteristics (e.g., sediment supply or coastal biodiversity) that have increased over the last thousand years and more intensively for 4 kyrs in western France (e.g., Gaudin, 2004; David, 2014). However, producing representative records of local anthropogenic influences can be challenging depending upon where the sedimentary archive is retrieved. For instance, local-scale or regional-scale paleo-reconstructions depend on the proximal or distal position of the sediment cores. Furthermore, the anthropogenic signal is less transmitted to offshore depths (hemipelagic sediments) than to proximal sedimentary sinks (e.g., continental lakes, coastal environments or estuarine bays). Yet, as recently shown by the studies of Lambert et al.

86 (2017) and Ganne et al. (2016) on modern sediments from the Bay of Brest and Loire estuary

87 (western France), respectively, anthropogenic pollen signals (*Cerealia* around 1%) suffer

88 from an over-representation of arboreal pollen grains relative to the actual vegetation cover on

89 the watersheds. Along the western European margin, it is therefore critical to select archives

90 mitigating the proximity of continental sources with non-biased sedimentary records. To that

91 end, the northern shelf of the Bay of Biscay (around 100 m water depth), located in a

92 transitional domain, appears ideal for investigating Holocene rapid and long-term

93 paleoenvironmental changes with a combined land-sea approach (Naughton et al., 2007;

94 Mojtahid et al., 2019).

95 In this study, we investigate the CBT-CS11 core, retrieved in the northern part of the Bay of

96 Biscay (BoBy; northern part of the *Grande Vasière* mid-shelf sediment patch). Mojtahid et al.

97 (2019) recently published their results on benthic foraminiferal content, benthic oxygen and

98 carbon stable isotopes on epibenthic species *Cibicides refulgens*, grain-size analyses and XRF

99 data. Their stable oxygen isotope measurements on *C. refulgens* showed a significant shift

100 around 3.5–2.5 ka BP, which they interpreted as resulting from the onset of the modern winter

101 thermohaline front. Here, we present new and complementary high-resolution records of

102 dinoflagellate cyst data, pollen assemblages and benthic foraminiferal stable isotopic data on

103 *Ammonia falsobeccarii*. By combining our dataset with previously published geochemical and

104 sedimentological data from the CBT-CS11 core, and other sediment archives from the BoBy

105 and North Atlantic basin, our Holocene study aims to: i) document the hydrographical

106 changes on the BoBy shelf together with vegetation changes in north-western France

107 watersheds, and ii) place those changes in the complex paleoceanographic and paleoclimatic

108 context of the North Atlantic basin. This approach allows us to suggest synoptic mechanisms

109 explaining the main drivers for precipitation and flood regimes over the last 7 kyrs in the

110 studied region. Ultimately, our results will help the archaeological community integrate

111 climate forcings into the framework of settlements and withdrawals from ancient coastal sites

112 in the region since the Neolithic period.

113

2. Environmental context of the Bay of Biscay

2.1. The hydrographic pattern

The Bay of Biscay (BoBy) is an open oceanic basin in the north-eastern Atlantic Ocean, fringed by the Spanish and French coasts (Figure 1). Today, seasonal atmospheric dynamics (Isemerand Hasse, 1985; Pingree and Le Cann, 1989) and high river discharges (e.g., Lazure and Jégou, 1998; Lazure et al., 2008; Ferrer et al., 2009) lead to a complex system of coastal currents where residual shelf currents mainly depend on wind driven, tidally induced and density driven flows (e.g., Vincent and Kurc, 1969; Pingree and Le Cann, 1989; Koutsikopoulos and Le Cann, 1996; Castaing et al., 1999).

More precisely, the circulation of the BoBy shelf can be schematized as follows (Charria et al., 2013; Figure 1b): in winter (October to March), a SW-dominant wind regime forces a SE to NW shelf current (with more intense currents from October to December) while, in summer (April to September), dominant winds from the NW sector force a NW to SE shelf current (with greater shelf currents from July to September). From mid-autumn to early spring (thus including winter as a whole), intense river flows associated with sustained wind activity maintain this region under the influence of the northward plumes of the Gironde and Loire rivers along the coast, with relatively low salinities between the coast and the 100 m isobath, at around 20–40 km from the coast. Freshwater discharges from the main rivers (Loire, Gironde, Vilaine and Adour; annual mean flow around 4,200 m^3/s) in surface layers thus induce steep density gradients driving a poleward circulation (about 10 cm/s) modulated by wind forcing (Lazure and Jégou, 1998; Lazure et al., 2008).

An along-slope seasonal current, occurring between the autumn and winter, is also characterized by cyclonic circulation (Pingree and Le Cann, 1989) and an intensified poleward surface flow (Iberian Poleward Current, IPC; Figure 1b). This warm and saline current (Frouin et al., 1990; Pingree and Le Cann, 1992a,b; Solabarrieta et al., 2014) can extend up to the Armorican upper slopes (western France; Le Cann and Serpette, 2009; Garcia-Soto and Pingree, 2012).

2.2. Precipitation, river discharges, winter thermohaline front

The coastal environments of north-western Europe are connected to the main Atlantic atmospheric regimes (e.g., North Atlantic Oscillation, NAO; East Atlantic pattern, EA). In Brittany, these weather regimes and North Atlantic Sea Surface Temperatures (SSTs), are the main mechanisms that drive the oceanic-rainfall regime, i.e., precipitation patterns and related river discharges (Tréguer et al., 2014), as well as storminess (van Vliet-Lanoë et al., 2014). During positive NAO modes, northern Europe generally has milder and wetter conditions and has the opposite during negative modes (Hurrell, 1995; Hurrell et al., 2003). Present-day environmental conditions in northern Europe (i.e., continental climate, as well as sea-surface temperature and salinity changes) are thus strongly impacted by the NAO and associated changes in seasonal precipitation and fluvial discharge regimes (Castaing et al., 1999; Charria et al., 2013; Le Boyer et al., 2013; Tréguer et al., 2014). At the Holocene scale, previous studies have discussed the possible role of the "NAO-like" pattern in westerly storm activity within the north-eastern Atlantic area (van Vliet et al., 2014; Goslin et al., 2018, 2019; Pouzet et al., 2018) as well as in sea-surface and bottom hydrological conditions in the northern (Zumaque et al., 2017; Durand et al., 2018; Mojtahid et al., 2019) and southern BoBy (Garcia et al., 2013; Mojtahid et al., 2013; Mary et al., 2017).

Modelling work suggested that, in winter, the Loire estuarine plume completely covers the Armorican shelf in the BoBy (Lazure and Jégou, 1998). Maximum (/minimum) values of river flows are greater than 1,500 m^3/s during winter-early spring (/<300 m^3/s during summer) (hydro.eaufrance.fr; Castaing and Allen, 1981). The confluence of marine and fluvial water bodies (turbid plumes; Jouanneau et al., 1999; Lazure and Jégou, 1998), then induces a winter thermohaline front that vertically separates bottom oceanic waters from surface freshwaters (Castaing et al., 1999; Yelekci et al., 2017), and takes over with increasing summer temperatures (Puillat et al., 2004). Consequently, a freshwater front also forms horizontally along the 100 m isobaths in the BoBy (dotted line in Figure 1b), which will hereafter be referred to as the "winter horizontal thermohaline front".

2.3. The "Grande Vasière" deposit

The winter horizontal thermohaline front limits the offshore diffusion of continental sediments, inducing the concentration of fine fluvial sediments within a massive mud patch (225 km by 40 km long, ~100 m deep; Figure 1b) referred to as the *Grande Vasière* (GV; Dubrulle et al., 2007). The GV designates the upper part of the Holocene sediment accumulation that built up at a rate of 0.1 to 0.2 cm/year (Lesueur et al., 2001) from the sedimentary infilling of the Tertiary substratum during the last marine transgression (Bourillet et al., 2006). Today, the GV deposit represents a seasonal compromise between a winter period of sediment advection fed by fluvial supply, and a period of higher sediment settling under weakened remobilization through wave actions (storminess and distant swell) between April and September (Dubrulle et al., 2007).

Sediment grain size is spatially heterogeneous over the GV, with finer sediments brought in by fluvial turbid plumes (Jouanneau et al., 1999; Dubrulle et al., 2007). The Loire River represents the second largest fluvial input volume after the Gironde (0.5–0.6.10^6 t/yr) and contributes about 24% of the solid sediment charge entering the whole BoBy (Jouanneau et al., 1999). In the northern part of the bay, the Loire and Vilaine Rivers together represent 95% of the BoBy watersheds. Up to 90% of the nutrient contribution in the northern part of the Armorican shelf comes from the Loire River, Vilaine River and southern Brittany coastal river discharges making smaller secondary contributions (Guillaud et al., 2008).

3. Material and methods

3.1. CBT-CS11 study core and benthic foraminiferal analyses

The CBT-CS11 core (47°46.429'N; 4°25.308'W; 73m depth; 3.96 m long; Figure 1) was retrieved using a Calypso-Genavir corer during the CABTEX cruise (Ifremer) of the R/V *Pourquoi Pas?* in June 2010 (Dussud, 2010). The lithological log of the core, CaCO$_3$-free grain-size analyses and XRF data (1 cm resolution) are fully described in Mojtahid et al. (2019), allowing the precise characterization of the deposits through time. Benthic foraminiferal assemblages have also been published in Mojtahid et al. (2019), with stable oxygen and carbon isotopes measured on the epibenthic species *Cibicides refulgens*, which was hand-picked from the 150–250 μm fraction (113 analyses, PSO, Plouzané, Table 2). In this study, we present a new isotopic dataset based on 101 analyses (~3–4 cm spacing; ~74 yr resolution) of *Ammonia falsobeccarii*, also hand-picked in the 150–250 μm and analysed at the PSO (Table 2). The external reproducibility (1σ) on repeated measurements of NBS19 international standard is ±0.04‰ and 0.09‰ for δ^{13}C and δ^{18}O, respectively.

3.2. Palynological analyses

A total of 114 samples (mean spacing of 3 cm between each) allowed us to reconstruct palynological assemblages with an optimal minimum (/mean) resolution of 20 years (/70 years). The same palynological procedure was applied for dinocyst and pollen extraction so as to allow direct comparison between terrestrial (pollen, spores and freshwater microalgae) and marine (dinocysts, other marine microalgae and foraminiferal linings) microfossils on the same palynological slide, thus avoiding chrono-stratigraphical issues. Palynological treatments (EPOC laboratory, Bordeaux University) were conducted on the < 150 μm fraction following the protocol of de Vernal et al. (1999) (Data in Brief).

A minimum of 300 dinocysts and 200 pollen grains were counted per level. In case of over-representation of a taxon (here *Lingulodinium machaerophorum* for dinocyst assemblages), counts were prolonged until at least 100 other specimens were found, keeping in mind that the threshold of 100 individuals is required to identify 99% of major species (> 5%) (Fatela and Taborda, 2002). Palynomorph percentages (%) and concentrations (taxa/cm^3) were then calculated (Table 2). Palynological taxonomical diversity was quantified by statistical analyses using the "Past version 1.75b" program (Hammer et al., 2001; indexes explained in Harper, 1999) (Table 2). In this study, we also established palynological ratios used for the

224   discussion of the main results (briefly detailed in Table 2) based on statistical analyses and
225   described in Data in Brief.
226

3.3. Radiocarbon dates

228   By adding four more AMS-^{14}C dates (three on lamellibranches and one on *Turritella*
229   *communis*) to those from the study of Mojtahid et al. (2019), we were able to build a robust
230   chrono-stratigraphy based on 25 dates; six dates being excluded from the final age model
231   (Table 1, Figure 2a). All dates were calibrated (Table 1) with Calib 7.1 software, using the
232   calibration curve IntCal13 (Stuiver and Reimer, 1993; Reimer et al., 2013), considering a
233   reservoir age of -324 years to radiocarbon dates (age reservoir for western Brittany, Sein
234   Island, Mangerud et al., 2006). The age model was then established using the *Bchron* package
235   in R version 3.5.1 (Figure 2b), allowing the reconstruction of the last 7 kyrs with mean
236   sedimentation rates of 74 cm/kyr from the base of the core to 5.5 ka BP, 33 cm/kyr from 5 to
237   1.8 ka BP, and 72 cm/kyr from 1.8 ka BP to the top of the core (Figure 2a). The top of the
238   core is assumed to have been reworked because of chronological issues (Mojtahid et al., 2019;
239   Figure 2a). Also, in this study, three pollen grains of *Zea mays* were observed at 44, 47 and 54
240   cm. Around the BoBy, maize cultivation began in northern Spain and France in the 17th
241   century (Tenaillon and Charcosset, 2011), before really taking off in 1950. Thus, the rare
242   grains observed in marine cores tend rather to be from the post-1950 period. Even though our
243   numerous dates could support extrapolation to the top of the core, as a precaution, only data
244   up to 60 cm (0.5 ka BP in age) will be discussed in this manuscript.
245

4. Palynological results and their associated interpretation

The description of palynological results led us to consider three main limits (A, B and C; introduced in Figure 3), as well as five palynozones (CBT 1 to CBT 5; shown in Figure 4 only). These boundaries/zones were established based on pollen and dinocyst observations in terms of both concentrations and percentages. In the following discussion, only limits A to C will be placed on Figures 5 to 10 to maintain the same scope as in the result section of this manuscript. Raw data are available in Data in Brief with a full description of the multivariate analyses conducted on pollen and dinocyst communities with other environmental variables.

4.1. Dinoflagellate cysts

a. Diversity and concentrations

Thirty-nine different dinocyst taxa were identified in the whole core, with a mean species richness (Figure 3a) of 18 different taxa per slide. From the base of the core to limit A (296 cm), species richness was higher than the dataset average, then diversity was lower than average up to limit C (110 cm) and then continuously increased towards the top of the core (Figure 3a). The evolution of the diversity (Margalef index; Figure 3a) was anti-correlated with the trend of *Lingulodinium machaerophorum* percentages, which were higher between limits A and C, with the lowest diversity being recorded on both sides of limit B (200 cm) between 217 and 163 cm (yellow band on Figure 3) when *L. machaerophorum* percentages (Figure 3a) as well as concentrations and fluxes (Figure 3b) were the highest.

Total dinocyst concentrations (Figure 3b; as well as the dominance index: Figure 3a) were mainly influenced by *L. machaerophorum* occurrences and ranged between 450 and 10,500 cysts/cm^3, with mean values of around 3,300 cysts/cm^3. Therefore, we plotted the concentrations of *L. machaerophorum* against the concentrations of other dinocysts to discriminate the respective parts occupied by this species and by the rest of the community (Figure 3b). Up to limit A, total concentrations of the other dinocysts were higher than *L. machaerophorum* ones. They, then followed a similar pattern between limits A and C, except in the interval "217–163 cm", which was characterized by the highest *L. machaerophorum* concentrations (~4,130 cysts/cm^3) and fluxes (~140 cysts/cm²/yr), while the other cysts did not show any major variations. Finally, from limit C onwards, concentrations of the other dinocysts were highest (~5,000 cysts/cm^3 from 110 cm; Figure 3b).

b. Dinocyst assemblages and dinocyst-zones

Overall, dinocyst assemblages were dominated by 10 autotrophic taxa: *L. machaerophorum*, *Spiniferites ramosus* (group of *S. ramosus* and *Spiniferites bulloideus*), *Operculodinium centrocarpum*, *Spiniferites lazus*, cysts of *Pentapharsodinium dalei, Spiniferites elongatus*, *Spiniferites mirabilis*, *Spiniferites bentorii*, *Spiniferites delicatus*, *Spiniferites membranaceus* (group of *S. membranaceus* and *Spiniferites belerius*), and two heterotrophic taxa including *Echinidinium* spp. and *Selenopemphix quanta* (group of *S. quanta* and *Protoperidinium nudum*) (Figure 4a). The five dinocyst zones (labelled from CBT 1 to CBT 5; Figure 4a) were related to the fluctuations of major cyst taxa percentages. First zone CBT 1 was characterized by the dominance of *S. ramosus*, *O. centrocarpum*, and cysts of *P. dalei*, revealing decreasing trends in parallel with the progressive rise of *L. machaerophorum* percentages (Figure 4a). Second zone CBT 2 was marked by a strong increase of *L. machaerophorum* percentages from around 50 up to 90% at the top of the zone (Figure 4a). *S. ramosus*, *O. centrocarpum* and *S. elongatus* are still abundant and their percentages gradually decreased to the end of the zone. From limit B (CBT 2-CBT 3 transition), *L. machaerophorum* percentages decrease onwards. *S. lazus* increased during CBT 3, while oceanic taxa (association *O. centrocarpum - S. elongatus*) no longer reached values as high as before the *L. machaerophorum* peak. Zone CBT 4 was characterized by the highest percentages of cysts of *P. dalei* while CBT 5 was marked by maximal values of *S. ramosus,* although percentages of *L. machaerophorum* were still significant across both zones.

4.2. Pollen assemblages

a. Diversity and concentrations

A total of 70 different pollen taxa were identified in the core as a whole, with a mean species richness (Figure 3c) of 18 different taxa per slide. Species richness was slightly lower than 20 before limit C and reached 20 to 30 taxa per slide immediately after. This increase in diversity was associated with the opening of the landscape (*Quercus* drop; Figure 3c) and the diversification of herbaceous plants. Mean total pollen concentrations were around 2,800 grains/cm^3 (ranging between 500 and 16,400 grains/cm^3), the highest values being representative of major peaks found between limits A and B, as well as in the top 60 cm. Total pollen concentrations are mainly driven by trees (especially *Quercus)*. In addition to the type of vegetation cover, pollen production and river transport are the main factors influencing the concentration of pollen grains. Thus, seasonal synchronization between these

two factors likely leads to much higher pollen fluxes. A disconnection between river inputs and the pollination period should have led to an increase of other palynomorph fluxes at the expense of pollen grains. It is interesting to note that until limit B, pollen concentrations were higher than dinocyst ones (Figure 3d), and after limit B, total percentages of tree pollen declined in parallel with increasing fluxes of *L. machaerophorum* and lower pollen grain fluxes to the shelf. From limit C, the major observations were higher pollen concentrations and fluxes, as well as a diversification driven by grassland taxa.

b. Pollen assemblages and pollen-zones

Zone CBT 1 (Figure 4b) was characterized by the dominance of arboreal pollen, mainly *Quercus* and *Corylus*, *Ulmus*, *Tilia* and *Alnus* being already present. Zone CBT 2 (Figure 4b) was marked by a slight increase of riparian trees (especially *Alnus*), *Betula*, and *Corylus,* with maximal values of *Alnus* percentages being reached at the end of the zone concomitantly with atypically high percentages of *L. machaerophorum*. Zone CBT 2 also showed a slight increase of Poaceae as well as the first discrete occurrences of cultivated taxa (i.e., *Cerealia*, *Secale cereale*, *Fagopyrum* at 224–227–230cm). Zone CBT 3 (Figure 4b) was then characterized by a continuous and rather high occurrence of *Fagus*, while thermophilic trees *Ulmus* and *Tilia* progressively faded out. This classic subboreal signature (Morzadec-Kerfourn, 1974) is the expression of the mid-Holocene freshening and increasing winter precipitations induced by the general decreasing summer insolation at 65°N (Naughton et al., 2007). Across Zone CBT 3 (Figure 4b), *Corylus* and *Alnus* percentages decreased, with *Betula* staying stable. Zone CBT 4 (Figure 4b) was marked by the highest values of Poaceae, ruderal plants and *Cerealia*, while mixed oak forest declined and *Fagus* nearly disappeared from the record. *Pinus* significantly increased in zone CBT 5, potentially indicating the appearance of pine forests in the 16th century.

5. Discussion

5.1. Offshore-nearshore dinocyst communities and the freshwater front in the northern Bay of Biscay

a. Comparing offshore-nearshore dinocyst communities in the northern Bay of Biscay

Dinocyst ecology has been thoroughly described through the progressive development and compilation of Atlases of modern cyst distribution (Rochon et al., 1999; Marret and Zonneveld, 2003; Zoneveld et al., 2013). Nonetheless, there remains a need to better understand the paleohydrological signature of this complex group along onshore-offshore gradients and in the specific case of sediments from stratified, frontal and mixed-water regions (Marret et al., 2004). In order to discuss ecological changes within a marine as opposed to a continental context, we compared dinocyst data from three sediment cores strategically located along a marine (distal or offshore) to coastal (proximal or onshore) transect across the BoBy (Figure 5): i) the full-oceanic MD95-2002 core (2,174 m water depth; Zumaque et al., 2017; Figure 1b) was directly influenced by the North Atlantic Circulation (Frew et al., 2000); ii) the shelf CBT-CS11 core (73 m water depth; this study; Figure 1b) was under mixed oceanic and winter fluvial influences; iii) the coastal "A" core, collected within the Bay of Brest, comes from a shallow macro-estuarine environment (8 m water depth; Lambert et al., 2019; Figure 1b). By including different bathymetric ranges from the same temperate latitudes, we accounted for potential changes in hydrographical and/or stratification conditions that may have resulted from the Holocene relative sea level (RSL) rise under variable climate and/or anthropogenic forcings. To account for the over-representation of *L. machaerophorum* in coastal mudflats, percentages of other cyst taxa were represented for the A and CBT-CS11 cores without considering *L. machaerophorum* counts in the main dinocyst sum (Figure 5).

b. General observations

Along Brittany's coasts, the understanding of the modern distribution of coastal-oceanic dinocyst communities was initiated by studies such as those of Rossignol (1964, 1969), Reid (1974), Morzadec-Kerfourn (1974, 1977), and Wall et al. (1977), which have been recently complemented by Ganne et al. (2016) and Lambert et al. (2017). Previous studies showed the dinocyst groups of the oceanic zone (>100–150 m water depth, outer-neritic or neritic-oceanic assemblages) to be characterized by *Impagidinium aculeatum*, *O. centrocarpum, S. mirabilis,*

and *S. elongatus* (with *S. ramosus* and *S. bulloideus* in addition), with *I. aculeatum* being restricted solely to full-oceanic waters. In the coastal zone (inner-neritic), the association *S. ramosus-S. bulloideus-S. bentorii* was shown to be predominant, with *S ramosus-S. bulloideus* being more specifically characteristic of the whole Iroise Sea (Figure 1b). Finally, the estuarine zone was shown to be characterized by *L. machaerophorum* until the upper part of the tidal zone (Morzadec-Kerfourn, 1977), which corresponds to this species' tolerance of large drops in salinity and its proliferation in brackish environments (Reid, 1975; Morzadec-Kerfourn, 1977, 1992, 1997). The presence of these ecological groups is shown on Figure 5 by the green colour (A core) to the purple colour (MD95-2002 core) for selected major cyst taxa, making it possible to reveal the main estuarine to full-oceanic taxa found in the studied area. Concerning CBT-CS11 cyst data (shown in pink in Figure 5), there is some evidence for stratified water conditions in a shelf environment subject to both continental and oceanic influences: i) estuarine to coastal quasi-monospecific assemblages of *L. machaerophorum*, ii) inner-neritic assemblages characterized by the association *S. ramosus-S. bulloideus,* iii) outer-neritic assemblages characterized by the association *O. centrocarpum - S. mirabilis - S. elongatus*, as well as iv) no full-oceanic *Impagidinium*-type observations. Offshore (MD95-2002), open-ocean taxa such as *I. aculeatum* (for temperate to subtropical environments) and *B. tepikiense* (for northern seasonally contrasted Atlantic environments; Rochon et al., 1999; Marret et al., 2004) are dominant while they are absent at mid-shelf depth (core CBT-CS11).

c. *L. machaerophorum*, tracer for freshwater plumes under phosphate deficiency?

At offshore locations (core MD95-2002), *L. machaerophorum* was almost absent during the Holocene (always lower or equal to 2%, except between 4.5 and 2.5 ka BP when it just reached 5% in some periods; Figure 5). This is consistent with the fact that offshore surface conditions are influenced by the general North Atlantic circulation, while the circulation on the continental shelf is influenced by mixed fluvial/tidal currents restricted to the coast. In modern sediments, this taxon formed up to 30% of total cyst assemblages by 100 m water depth but barely reached 5% directly after 150 m water depth in full-oceanic Atlantic associations (Andreieff et al., 1971; Williams, 1971). 90 to 96% of *Lingulodinium polyedrum* resting cysts, i.e., *L. machaerophorum,* were found in surface sediments from north-western France estuaries (Vilaine, Loire, and Bay of Brest; Ters et al., 1968; Morzadec-Kerfourn, 1976, 1977; Ganne et al., 2016; Lambert et al., 2017). A front may thus prevent the offshore dispersion of *L. machaerophorum* outside the region under influence of freshwater plumes (Costoya et al., 2016). This freshwater front may act as a major hydrological barrier

Interestingly, *L. machaerophorum* percentages from the Bay of Brest (core A) and South Brittany shelf (core CBT-CS11) showed equivalent patterns with a clear shift at 5.9 ka BP (limit A; Figure 5), most likely corresponding to a marked slowdown in the rates of the RSL rise identified at a regional scale (Morzadec-Kerfourn, 1995; Goslin et al., 2015; Stéphan et al., 2015; Garcia-Artola et al., 2018; Figure 2a). This inflexion of RSL rise-rates likely facilitated the encroachment and development of tidal flats and subsequent saltmarshes along the coasts, thus fostering the development of terrestrial sedimentation (e.g., Joly and Visset, 2009; Menier et al., 2010; Stéphan et al., 2019). The formation of brackish marshes along the estuaries may explain the proliferation of *L. machaerophorum* cysts. Major occurrences of this species were particularly seen within the 4–2 ka BP interval, both in terms of percentages and concentrations (yellow band on Figure 5). Massive encystments may be attributed to unfavourable conditions (e.g., drops in salinity) in a context of phosphorus deficiency. This hypothesis gains weight when we consider that concentrations of other dinocyst taxa and overall species richness remained low, between 4 and 2 ka BP (Figures 3b and 5).

d. Winter horizontal thermohaline front establishment

O. centrocarpum percentages reached around 40% offshore (core MD95-2002) before 3.3 ka BP (limit B, Figure 5; becoming inversely correlated with increasing *S. mirabilis* percentages at that time), and around 20% at mid-shelf depth (core CBT-CS11), suggesting a North Atlantic Current (NAC, Figure 1a) origin of this species (Turon, 1984; Rochon et al., 1999; Penaud et al., 2008). The decrease in *O. centrocarpum* at 3.3 ka BP in both cores may relate to a common hydrographic cause linked to a weaker NAC. Interestingly, while the oceanic *O. centrocarpum* pattern is similar in both shelf and hemipelagic cores, the oceanic *S. mirabilis* pattern (second major species in the MD95-2002 core) was not obvious beyond limit B on the shelf. CBT-CS11 was then characterized by rising percentages of *S. lazus*, followed after limit C by increasing values of cysts of *P. dalei*, both taxa rarely occurring within the deep-water core MD95-2002 at that time, while being found in the Central Celtic Sea at 118 m depth

(Marret et al., 2004). Along with the influence of the Iroise Sea (especially *S. ramosus*, Morzadec-Kerfourn, 1977), increasing presence of heterotrophic *S. quanta* with cysts of *P. dalei* from 1.2 ka BP (limit C) may indicate the existence of stratified high productivity conditions (Howe et al., 2010). In summary, the winter horizontal thermohaline front may thus be identified at 3.3 ka BP based on the pronounced disconnection of oceanic and shelf waters, the mid-shelf being characterized by enhanced stratification under increasing winter fluvial discharges, with a trophic change at 1.2 ka BP resulting from increasing nutrient bioavailability in surface waters.

5.2. Atlantic Meridional Overturning Circulation and subpolar gyre dynamics through the Holocene

a. The 5.9 ka BP limit: evidence of strong oceanic re-organization

The north-eastern Atlantic is a key climatic area requiring careful attention, particularly with regard to NAC vigour. This branch of the North Atlantic Sub-Polar Gyre (SPG; Sutton and Allen, 1997) affects the Atlantic Meridional Overturning Circulation (AMOC) by varying poleward heat transport intensity over time (Carton and Hakkinen, 2011). Some recently published data made it possible to synthesize the long-term Holocene trend considering AMOC dynamics (Figure 6). AMOC strength and SST south of Iceland were maximal until 6 ka BP (e.g., Eynaud et al., 2018; Ayache et al., 2018) before slowly decreasing (as shown by the general decline in bottom flow strength: Kissel et al., 2013). This breakdown in North Atlantic dynamics associated with hydrological reorganization occurred synchronously with the 5.9 ka BP limit previously discussed for the CBT-CS11 core and resulting from the slowdown of the RSL rise and the stabilization of estuarine banks. The final collapse of the Laurentide Ice Sheet (Dyke, 2004; Kaplan and Wolfe, 2006; de Vernal and Hillaire-Marcel, 2006) implies the start of the Labrador Sea convection (minimum of sea-ice concentrations in the eastern Fram Strait, northern Baffin Bay and Labrador Sea at 6 ± 0.5 ka BP, de Vernal et al., 2013), thus impacting the AMOC through reduced poleward heat transport to the Nordic Seas, and then contributing to the establishment of the modern AMOC (Hoogakker et al., 2011; Ayache et al., 2018). Simultaneously, reduced summer SSTs in the north-eastern Atlantic (MD95-2002 core; Zumaque et al., 2017; Figure 6) reflect the half-cycle of the precessional signal implying decreasing summer insolation at 65°N for 9 kyrs (e.g., Berger and Loutre, 1991; Ayache et al., 2018).

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b. Eastern North Atlantic Central Water signature

Superimposed on this long-term RSL rise, AMOC, and insolation trends, North Atlantic SPG dynamics can be reconstructed at a sub-orbital timescale from marine sediment archives in the northern Atlantic Ocean (e.g., Giraudeau et al., 2010; Solignac et al., 2006, 2008; Zumaque et al., 2017; Ayache et al., 2018; Mojtahid et al., 2019). Millennial timescale events (Bond et al., 1997, 2001), as well as multi-decadal variability, related to internal modes of atmosphere-ocean teleconnection such as the "NAO-like" mechanism have exerted a control on the latitudinal position of westerly storm tracks (Sorrel et al., 2012; van Vliet et al., 2014; Goslin et al., 2018, 2019) and may have strongly impacted Atlantic gyre dynamics throughout the Holocene (Thornalley et al., 2009; Figure 6). Since the CBT-CS11 core was influenced by Eastern North Atlantic Central Waters (ENACW), which were themselves influenced by the NAC, Mojtahid et al. (2019) discussed the benthic δ^{18}O signal of *Cibicides refulgens* as a proxy for ENACW waters mainly responding to subpolar rather than subtropical gyre influences. To complement these interpretations and go further, we produced another series of δ^{18}O measures on the benthic foraminifera *Ammonia falsobeccarii* (Figure 6). Higher isotopic values on both species, here highlighting mainly higher salinities (such as tropical ENACW today; Voelker et al., 2015; Figure 6), match the density anomalies at sub-thermocline depths recorded in the southern Iceland basin (Thornalley et al., 2009; Figure 6). However, the two benthic isotopic records diverge at 3.3 ka BP (limit B; Figure 6), with the *C. refulgens* signature being characterized by a shift towards a new oscillating salinity state with heavier values after 3.3 ka BP. Mojtahid et al. (2019) interpreted this shift as an overall cooling state that occurred under the establishment of the winter thermohaline front (Figure 6). Since *C. refulgens* is an epibenthic/epiphyte species, we hypothesize that it may reflect an isotopic signature more characteristic of the surface (being transported by currents after first becoming attached to littoral plants) and thus a cooling related to fluvial water advections being plated to the coast up to the 100 m isobath. *A. falsobeccarii*, which is part of the surficial infauna, would calcify in equilibrium with poral waters, being less influenced by seasonal surface conditions related to river plumes and more by polar (ENACWP) than tropical (ENACWT) oceanic signatures (cf. Figure 1a). The *C. refulgens* isotopic record confirms the 3.3 ka BP limit as the main time when the modern winter thermohaline front was established (Mojtahid et al., 2019). *A. falsobeccarii* will be used as a SPG dynamic index in the following discussion (Figure 7).

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c. Subpolar gyre dynamics and Bond events

As a second step, we compared the *A. falsobeccarii* record with Ice-Rafted Debris (IRD) data in the North Atlantic (Bond et al., 2001; Figure 7). From the mean value of both datasets, we established an anomaly scale: red (less IRD–weaker SPG, with a more pronounced ENACWT signature) and blue (more IRD under stronger EGC–stronger SPG, with a greater influence of ENACWP at our studied site and of the NAC in the Nordic Seas). The two signals show a good concordance, with enhanced SPG strength at times of peaks in IRD, especially across Bond events 4, 2 and 1 (Figure 7). These three major intervals (6.4–5.1, 3.3–2.7, and 1.6–1.2 ka BP) were coded with blue bands for the following discussion and the red/blue scale (SPG dynamics) based on the *A. falsobeccarii* $\delta^{18}O$ oscillating signal (cf. Figure 7) was placed in parallel with other proxies to improve the mechanistic understanding of climatic and hydrographic changes and related environmental impacts over the last 7 kyrs (Figures 8 to 10).

5.3. Oceanic versus continental influences on the Bay of Biscay shelf

The BoBy exhibits three kinds of hydrographic regime depending on the bathymetry: the abyssal plain, the continental slope and the northward widening continental shelf reaching 160 km on the Armorican shelf. The BoBy is thus influenced by large-scale oceanic circulation (which we will refer to as "oceanic influence") and local forcing implying seasonal wind regimes as well as river discharges and run-off (which we will refer to as "continental influence"). It is worth keeping in mind that our observations filter the mesoscale and interannual variability to depict multi-decadal scenarios of environmental forcing and related impacts.

a. From 7 to 5.9 ka BP (~Early–Middle Neolithic)

During this period, pollen concentrations were higher than dinocyst ones and seasonal synchronization between pollen production and river transport is assumed because of high pollen fluxes (Figures 3d and 9). These may correspond to high arboreal pollination (higher summer insolation at 65°N) having been synchronous with fluvial discharges of the main rivers, thus implying higher precipitations during spring. In terms of sediment facies, we suggest that the generally coarser sedimentation (Zr/Al ratio, D50 CaCO$_3$ free; Mojtahid et

al., 2019), resulting from spring fluvial currents, took over the winter supply of fine material by fluvial turbid plumes. This hypothesis appears to be supported by the overall coherence we observe between grain-size tracers and summer SSTs reconstructed in the Bay of Biscay (core MD95-2002; Figure 8). Until 5.9 ka BP, stronger occurrences of the cosmopolitan-oceanic *O. centrocarpum* species, suggested here as a potential tracer for the NAC (Rochon et al., 1999), than occurrences of *L. machaerophorum* (ratio "*O. centrocarpum / L. machaerophorum*" on Figure 9), would reflect an increasing strength of the NAC at a time of stronger AMOC (e.g., Ayache et al., 2018). We further suggest that stronger humidity through the NAC may have amplified seasonal continental humidity in Western France during the hypsithermal. Therefore, in a high boreal summer insolation context (Holocene Thermal Maximum; e.g., Renssen et al., 2012), strong pollination of trees coupled with spring precipitations would be responsible for higher arboreal pollen fluxes to the shelf. We entitled this configuration "summer-prevailing mode" and suggest that a north-west to south-east shelf residual circulation was prevalent within the BoBy (Figures 8 and 11). At that time of still rapid RSL rise (Garcia-Artola et al., 2018), southward residual shelf currents may have dominated sea-surface circulation in the BoBy.

b. From 5.9 to 3.3 ka BP

At 5.9 ka BP, the reduced accommodation space on the shelf, as well as the stabilization of fluvial environments, favoured the development of alluvial plains and allowed the ripisylve to progressively colonize riverbanks (limit at 5.7 ka BP identified by Cyprien, 2002). This period of valley alluviation (increasing *Alnus* and *L. machaerophorum* percentages; Figure 9) corresponds to a still active poleward heat transport to the Nordic Seas via the NAC (as shown by the persistent high percentages of *O. centrocarpum*; Figure 8) and the rise of *Corylus* and *Betula* under increasingly fresher and wetter climate conditions. Thanks to the development of riparian hydrophilous shrublands along freshwater bodies, the stabilization of fluvial systems (i.e., development of vegetation on riverbanks and their fixation) may have implied: i) reduced sedimentation rates to the shelf by retaining solid and dissolved river inputs (Figure 9), and ii) increased brackish waters in coastal waters (major drops in salinity) as observed through *L. machaerophorum* cyst proliferation (Figure 9).

Two sub-periods can be identified within this time interval:

- 5.9 to 4 ka BP (~Recent–Late Neolithic): The sustained elevated abundances of *O. centrocarpum* and relatively coarse sedimentation may suggest mixed oceanic-continental influences with a non-oriented shelf residual circulation, referred to here as "autumn-prevailing mode" (Figures 8 and 11). This mode would have especially prevailed until 4 ka BP (equivalent values of neritic-oceanic and *L. machaerophorum* concentrations and fluxes, high tree pollen grain percentages; Figure 9). This period would correspond to the settlement and evolution of Recent and Late Neolithic coastal societies on the fringes of coastal zones (e.g., Molène archipelago; Pailler and Nicolas, 2019).

- 4 to 3.3 ka BP (~Early–Middle Bronze Age): This interval fits within the larger 4–2 ka BP interval identified in Figure 5 (yellow band). This latter also corresponds to a peculiar interval of generally higher winter SST and SSS (2 to 3 psu higher-than-average) within the MD95-2002 slope core (yellow band on Figure 6), which was synchronous with the strongest *L. machaerophorum* occurrences (Figure 9) and generally weaker SPG dynamics (Thornalley et al., 2009; Figures 6 and 9). Additionally, a shift at 4 ka BP from prevalently positive to prevalently negative NAO-like conditions until 2 ka BP was suggested from the study of a lake sediment record from south-western Greenland (Olsen et al., 2012; Figure 9). The long-term phase of recurrent negative NAO-like conditions may have resulted in an enhanced East Greenland Current and/or in some melting of the Greenland Ice Sheet according to Orme et al. (2018) who identified a major long-term SST cooling south of the Iceland Basin over the 4–2 ka BP interval. Our data tell a more complex story for this latter 4–2 ka BP interval and make it possible to divide it in three sub-periods. The 4–3.3 ka BP period constitutes its first phase and is characterized by negative NAO-like recurrent modes. Poleward flows have been thoroughly studied (Pingree and Le Cann, 1989; Koutsikopoulos and Le Cann, 1996) and are known to occur frequently within the BoBy, pulsing during the autumn and winter seasons (Charria et al., 2013). This along-slope circulation (IPC; top 350 m of the water column; Figure 1b) implies seasonal warmer conditions extending up to the Armorican slope, and it has been suggested that, today, southerly winds represent the main contribution to the IPC intensification over the upper slope and outer shelf, generating anomalously high winter SSTs (e.g., Pingree and Le Cann, 1992a,b; Le Cann and Serpette, 2009; Garcia-Soto and Pingree, 2012). Here, we thus suggest that, between 4 and 3.3 ka BP,

605   prevalent southerly winds may have promoted a northward IPC, resulting in higher

606   winter SSTs in the north-eastern Atlantic Ocean (MD95-2002; Figure 9). The highest

607   *I. aculeatum* percentages recorded within core MD95-2002 during this time interval

608   (Zumaque et al., 2017; Figure 5) reinforce the hypothesis of a major advection of

609   subtropical waters during this interval. This context may have promoted major winter

610   precipitation and thus major repeated flood events over the Loire riverbanks during the

611   winter seasons. It is noteworthy that Delaine et al. (2015), who studied the Loire

612   valley infilling near Nantes during the Holocene, reported a period of high erosional

613   regime and/or intense reworking denoting high hydrodynamics of the Loire River

614   from ~ 5.8 to 2.1 ka BP. In addition, a synthesis on the Loire showed a peak frequency

615   and/or magnitude of floods between 4.4 and 3.5 ka BP (Val d'Orléan; Arnaud-Fassetta

616   et al., 2010), concomitant with our observation.

617

618

619 c. From 3.3 to 1.2 ka BP

620 This period was characterized by a strong drop in Greenland air temperatures (Vinther et al.,

621 2006; Figure 8), large global temperature anomalies (Marcott et al., 2013; Figure 8), as well

622 as increasing annual precipitation and decreasing atmospheric temperature seasonality as

623 shown by pollen-based climate reconstructions conducted in north-western France (Core

624 VK03-58bis; Naughton et al., 2007; Figure 1b). At 3.3 ka BP, this change in precipitation

625 resulted in major winter river discharges (Stéphan et al., 2015) and a large decrease in oceanic

626 influence (major decline of *O. centrocarpum* percentages) in BoBy shelf waters. Finer

627 sediments (Figure 8) thus correspond to winter advection of fine sediments and spring

628 deposition under hypopycnal currents (similar to the present-day configuration: Charria et al.,

629 2013). The establishment of the winter horizontal thermohaline front is obvious here at 3.3 ka

630 BP and this configuration was named the "winter-prevailing mode" (Figures 8 and 11).

631 The 4–2 ka BP interval of prevalent negative NAO-like conditions is interrupted by the 3.3–

632 2.8 ka BP interval (Bond event 2; Figures 8 and 9) during which persistent positive NAO-like

633 conditions occurred, accompanied by enhanced SPG strength, decreased influence of the

634 warm and salty poleward current (lower winter SST/SSS offshore), and strengthened northern

635 Atlantic westerly storminess (Goslin et al., 2018; Figure 9). Regionally, this latter period

636 (Middle to Late Bronze Age) was characterized by a scarcity of coastal archaeological

637 remains. Indeed, it is generally accepted that the harsh meteorological conditions caused by

638 this period of climatic deterioration, accompanied with widespread dune-sand invasions of

coastal areas (e.g., Tisdall et al., 2013; van Vliet et al., 2016), may have caused the withdrawal of coastal societies from the shores during the winter season or even permanently (Stéphan et al., 2013, 2018). Among other adaptive possibilities, this may have encouraged some populations to turn more towards land cultivation rather than exploitation of marine resources (although salt producers were probably also farmers or herders). This is suggested by the decreasing occurrences of *Alnus* and *Corylus* pollen grains in our data (and further emphasized by the ratio of *Corylus* to *Quercus* (explained in Table 2) in Figure 9), which may reflect major phases of upland clearance (Figure 9). The anthropogenic origin of this pollinic observation is also indicated by the fact that no comparable shifts appeared during either Bond event 4 or 1 while, on the contrary, both pollinic tracers (*Alnus*, *Corylus*) tended to increase (Figure 9). Accounting for the synchronous trend of increasing sedimentation rates (Figure 9), the drops in *Alnus* and *Corylus* percentages around 3.3–2.8 ka BP, while *Betula* percentages remain stable, could indicate an anthropogenic impact on the landscape, with preferential human selection of alluvial taxa in a context of landscape opening (a continuing decreasing trend of arboreal pollen percentages following the increase of Poaceae as well as of *Plantago lanceolata*; Figure 4b).

d. From 1.2 ka BP onwards

From 1.2 ka BP, which also corresponds to the end of Bond event 1, a sharp shift was observed in both pollen and dinocyst communities (Figure 10). Cultivated, ruderal and adventive plants clearly indicate massive landscape opening after this point (Figure 10). The increase in the area under cultivation and pasture was thus established from the Middle Ages, as previously noted (Barbier and Visset, 1997; Cyprien, 2002; Joly and Visset, 2009; David, 2014). At this time, the increase in sedimentation rates may thus have resulted from rainwater runoff over bare watersheds. The human imprint on coastal wetlands also became strong, especially for drainage or water intakes (Joly and Visset, 2009).

Increasing concentrations of *S. quanta*, a heterotrophic taxon, and of cysts of *P. dalei* (Figure 10) could be explained by an increase in the supply of nutrients to the shelf, most likely provoked by the reduction of the forest cover and the subsequent increase of soil erosion and continentally derived organic matter. This may indicate the existence of stratified high productivity conditions (Howe et al., 2010). Indeed, cysts of *P. dalei* increase when upper water salinities are reduced throughout the year as a result of increasing: i) freshwater riverine inputs (Zonneveld *et al.*, 2013) and ii) phosphate concentrations within the upper water column (Zonneveld *et al.*, 2012). Because *Lingulodinium polyedrum* cyst formations are

favoured in cultures in a media replete in phosphate levels (Figueroa and Bravo, 2005), the massive nutrient, and especially phosphate, influx from 1.2 ka BP would contribute to explaining the sharp drop in *Lingulodinium machaerophorum* occurrences. At that time, it should also be noted that the highest concentrations of diversified dinocysts (without *L. machaerophorum*: ~5,000 cysts/cm^3; Figure 3b and 5) are recorded. The same trophic re-organization of coastal water bodies has recently been described in the Bay of Brest, though in much higher proportions, with sharp drops of *L. machaerophorum* percentages related to intensive agriculture practices after World War II (Lambert et al., 2018).

5.4. Understanding western European river floods

a. Effects of climate-driven factors on anthropogenic palynological evidence

As a first general observation, the first clear retreat of mixed temperate forest was recorded between 4.5 and 4 ka BP, indicating the beginning of the landscape opening and onset of inland agro-pastoral practices (as shown by the presence of ruderal plants such as *Rumex* and *P. lanceolata* accompanied by first low *Cerealia* occurrences, Figure 10). This is consistent with other pollinic studies carried out in north-western France (e.g., Gaudin, 2004; David, 2014; Fernane et al., 2014, 2015), i.e., with the transition from the Neolithic to the Bronze Age cultural periods (Figure 10). The next major step in landscape opening dynamics occurred at the Bronze to Iron Age transition, shown well by the increase of ruderal and cultivated plants, as well as by a higher "dinocyst (without *L. machaerophorum*) to pollen" ratio (Figure 10). The rise of this ratio is probably based on two non-exclusive factors: i) a higher dinocyst productivity induced by nutrient enrichment of coastal waters, and ii) a smaller contribution of the strongest tree pollinators to the pollen assemblages induced by the clearing of regional woodlands.

It is interesting to observe, however, that the most representative indices of anthropogenic impacts increase during periods of weakened SPG dynamics (or higher subtropical influence, red/blue scale on Figure 10). In other terms, palynological tracers of anthropic activity appear closely associated with more favourable climate conditions that allowed their transport and record to be left in marine sediments. This hypothesis is further confirmed by the fact that *Echinidinium* spp. percentages follow a pattern equivalent to the one followed by ruderal plants or Poaceae (Figures 4a and 10). The fluviatile (or river-plume) sensitive nature of *Echinidinium* spp. (Zonneveld et al., 2013) confirms that strengthened nutrient-enriched river discharges occurred during time intervals characterized by weakened SPG activity. This

illustrates the difficulty of accurately tracing past human dynamics using pollen indicators of anthropisation within marine sediments. Indeed, their occurrences may first be the expression of higher precipitation capable of transporting heavy pollen grains to the sea. These indices nonetheless seem to adequately depict the main trends of anthropogenic impacts in regional watersheds from the start of the Bronze Age and later, as illustrated by the regular Poaceae profile (dotted line in Figure 10: theoretical Poaceae trend).

b. An atypical signal of arboreal expansion during the 1.8–1.2 ka BP interval

When looking at the general Poaceae trend since the start of the Bronze Age (Figure 10), it is tempting to connect the arboreal rise between 1.8 and 1.2 ka BP with a major human decline that coincided with the Roman period and transition to the start of the Middle-Ages (Lambert et al., pers. comm., for the Bay of Brest). For instance, working on a coastal sedimentary archive (southern edge of the Armorican Massif), Joly and Visset (2009) observed the reappearance of the oak during the Gallo-Roman period (as also observed in the Mayenne and Loire valleys, Barbier and Visset, 1997; Ouguerram and Visset, 2001; Cyprien, 2002), and suggested a link with possible strategies of forest management in reaction to forest over-exploitation during the Iron Age. However, the sharp increase in sedimentation rates at 1.8 ka BP (Figure 10) that we attributed to human-induced soil erosion, suggests hydrographic changes could be responsible for this atypical arboreal re-increase.

Several phases of SPG strengthening took place within the 1.8–1.2 ka BP interval (major climate deterioration of Bond event 1; Figure 10). This climatic context probably also had consequences for the arboreal *versus* Poaceae signatures; tree pollen grains being better preserved in marine sediments while, as previously discussed, the Poaceae signature is enhanced by stronger fluvial discharges. The impact of oceanic *versus* river processes on tree *versus* Poaceae occurrences and preservation would also be clearer in the context of an already opened landscape. This may explain the strong Poaceae decline observed during Bond event 1, but also the weaker ruderal signature observed during Bond event 2, while Bond event 4 occurred in a period during the Neolithic, when major forest clearings were not yet observed.

Interestingly, during the 1.8–1.2 ka BP interval, percentages of fluviatile-sensitive *Echinidinium* spp. taxa as well as the dinocyst to pollen ratio were characterized by sharp drops, suggesting a small impact of river discharges to our study site. Also, a recent study from Durand et al. (2018), carried out at the mouth of the Loire River for the Late Holocene, discussed the influence of positive NAO-like configurations responsible for lower terrigenous

740   inputs to the sea in a period known for increased storminess. However, even if the absence of

741   anthropogenic indices and the peak in arboreal pollen grains may not result from human

742   causes (i.e., forest management, land abandonment in a context of wars or invasions), we

743   cannot exclude that this climate event could have had serious consequences for coastal and

744   inland societies because of storms and stronger humidity under recurrent positive NAO-like

745   conditions.

746

747   c. Factors required for major Holocene Loire discharges

748   Interestingly, major peaks of palynomorph fluxes (/drops of anthropogenic indexes), make it

749   possible to understand the environmental conditions required for increasing (/decreasing)

750   fluvial discharges from major north-western French rivers (Figure 9). During Bond events,

751   strong positive NAO-like configurations are known to favour increased precipitation and

752   storminess, then fostering fluvial discharges in north-western Europe (as observed by Tréguer

753   et al., 2014, for the 1998–2013-time interval in the Bay of Brest). The opposite is true during

754   negative NAO modes. Here, palynomorph fluxes (Figure 9) generally increased during

755   periods characterized by weakened SPG dynamics and prevalent negative NAO-like

756   conditions (Figure 9). This would imply that, at the location of the studied site (south

757   Brittany), sediment supply is more influenced by river systems with watersheds extending

758   southwards. The Loire River, and probably the Gironde, may thus largely explain our

759   palynological concentration/flux records. Higher palynomorph fluxes (dates given in red in

760   Figure 9) generally coincide with subtropical gyre strengthening and negative NAO-like

761   conditions. On the general "summer-prevailing", "autumn-prevailing" and "winter-

762   prevailing" modes (Figure 8) linked with the long-term insolation trend (Berger and Loutre,

763   1991), we can therefore superimpose a millennial-scale mechanism implying SPG strength

764   coupled with natural atmospheric oscillations (Figure 11). Indeed, it has been demonstrated

765   that North Atlantic SPG response is strongly related to persistent NAO configurations even

766   though a large non-linearity exists regarding the NAO response to atmospheric forcing

767   (Lohmann et al., 2009). A steady weakening of the SPG was however found throughout the

768   integration of negative NAO modes in a modelling study by Lohmann et al. (2009), while

769   positive phases of the NAO strengthened the SPG with poleward advection of NAC waters.

770   This is notably due to the wind-stress implied by northern-located mean westerly storm tracks

771   (e.g., Giraudeau et al., 2010; Goslin et al., 2018). Stronger Loire River discharges from the

772   start of the Late Holocene would therefore represent a conjectural phenomenon of stronger

773   subtropical gyre influence under negative NAO-like modes. This latter scenario may have

been amplified by periods of solar minima (reduced solar activity or solar irradiance under lower magnetic waves; Steinhilber et al., 2009; Figure 8). Indeed, during solar minima, several observational revealed southward shifts of North Atlantic storm tracks towards central to southern Europe (south of the 50°N) as well as an increase of associated precipitation and flood frequency (e.g., de Jong et al., 2006, 2007; Costas et al., 2012; Laurenz et al., 2019). As far as our data is concerned, with the exception of some events (at 5.9, 3.4 and 1.3 ka BP), the correlation between solar forcing and palynomorph fluxes at a multi-decadal timescale is insufficiently significant, but was convincingly discussed for the mouth of the Loire River in a previous study (Durand et al., 2018).

6. Conclusion

Ecosystem resilience to natural hazards, as well as to human occupation or withdrawal from the coast, is a compelling issue across the Holocene. In the present study, we took advantage of the complex sedimentation context of the northern Bay of Biscay (BoBy) shelf, especially marked by the dual influence of both oceanic currents derived from the North Atlantic Current and winter fluvial discharges, to address several issues regarding the links between natural climate modes (including Atlantic subpolar gyre and North Atlantic Oscillation dynamics, storminess and floods) and the dynamics of terrestrial and marine ecosystems. Our study may therefore help the archaeology community to understand major phases of occupation or desertion of coastal sites on the western French coastal fringe, but also the climate community to place the Loire floods as observed today in a broader spatio-temporal context.

The high-time resolution (~70 years on average) multi-proxy analysis on the CBT-CS11 mid-shelf core revealed the complexity of the palaeohydrological and palaeoclimatic signals recorded over the last 7 kyrs. At 5.9 ka BP, we identified major reorganizations of the hydrological systems accompanying the stabilization of the sea-level rise and the slowdown of the Atlantic Meridional Overturning Circulation. We also revealed repetitive intensifications of the fluvial discharges, here mainly connected to the hydrological regimes of the Loire River, and showed the links between these latter events and increased winter precipitations during periods of enhanced subtropical gyre dynamics coupled with negative NAO-like modes. Among these events, major ones occurred within the 4–2 ka BP interval with probable repercussions for coastal societies from the Early Bronze and Iron Ages (access to marine food resources in spring, flooding risks during winter). In addition, within the 4–2 ka BP interval, the 3.3 ka BP appeared as the establishment of the winter horizontal thermohaline front in the BoBy shelf. Finally, we revealed major soil erosion and primary productivity increase since 1.8 ka BP (Roman Period) and more specifically since 1.2 ka BP (Early Middle Ages).

7. Acknowledgments

8. Table caption

Table 1: CBT-CS11 AMS-^{14}C dates. In black, dates previously published in Mojtahid et al. (2018). In bold and red: new dates from ARTEMIS received in March 2019. Grey cells represent levels averaged for the final age model. Dates in italic (with the annotation « * ») were rejected for the final age model (Figure 2).

Table 2: This table gathers CBT-CS11 data discussed in this study and describes the way data were obtained (methodology) and can be interpreted. It is worth noting that a Data in Brief paper complementary to this study describes multivariate analysis on which some taxa groups or ratios here listed were established.

9. Figure captions

Figure 1: a) Geographical map of the "HAMOC" database subdivisions (provinces) with the location of the selected sedimentary records for the HAMOC synthesis (Eynaud et al., 2018; Ayache et al., 2018) and the additional superimposed studied site CBT-CS11. **b)** Map illustrating the general surface circulation of the Bay of Biscay (Koutsikopoulos and Le Cann, 1996) and the extent of the Loire and Gironde catchment areas. Are indicated the locations of the CBT-CS11 core (studied site) and of the other cited cores in the text: VK03-58bis core (Naughton et al., 2007); A core (Lambert et al., 2019); MD95-2002 core (Zumaque et al., 2017). Map performed using the online EMODnet Portal for Bathymetry (http://www.emodnet-bathymetry.eu/) and adapted from Mojtahid et al. (2019).

Figure 2: Age model for the CBT-CS11 core. **a)** Age-Depth plot of all dates obtained on the core allowing to address three main trends in sedimentation rates. The plot is represented in parallel with: relative sea level (RSL) heights for southern Brittany from García-Artola et al. (2018), northern Europe (western Denmark) paleo-tempetuosity as reconstructed by the Aeolian Sand Influx (ASI) (Goslin et al., 2018), Bond Events as reconstructed through hematite-stained quartz percentages with stacked North Atlantic Ocean cores (Bond et al., 2001) and Total Solar Irradiance (TSI; Steinhilber et al., 2009). Blue horizontal bands represent stacked Eastern European Atlantic Storm Events (Pouzet et al., 2018) while dark blue vertical lines to the right only point to the southern Brittany paleostorminess record (Yeu island; Pouzet et al., 2008). The superimposition of both information allows to establish the

858   vertical storm scale also shown in Figures 8 and 9. **b)** Final age model established using the

859   *Bchron* package in R version 3.5.1. **c)** Cultural subdivisions for western Brittany.

860

861   **Figure 3:** CBT-CS11 palynological data against depth (cm): Diversity indexes (Table 2) are

862   drawn in blue for dinoflagellate cysts (**a**, in parallel with percentages of the major species

863   *Lingulodinium machaerophorum*) and in green for pollen assemblages (**c**, in parallel with

864   percentages of *Quercus* and Total Trees); Concentrations (in linear scale) and fluxes (in

865   logarithmic scale) for dinocysts (**b**) and pollen grains (**d**). The yellow horizontal band

866   underlines the atypical elevated signatures (percentages, concentrations, fluxes) of *L.*

867   *machaerophorum*. A to C horizontal dotted lines consist in the main limits between the four

868   palynozones discussed in the manuscript. To the left, all radiocarbon dates are represented in

869   Cal BP with rejected dates in italic-grey and selected dates for age model in bold-red.

870

871   **Figure 4:** CBT-CS11 palynological data against depth (cm): major taxa occurring with values

872   higher than 2% in palynological assemblages. **a)** dinoflagellate cyst (dinocyst) and **b)** pollen

873   assemblages. Palynozones CBT 1 to CBT 5 are shown with CBT 5 being included in the

874   probably reworked part of the top 60 cm of the studied core (grey band). A to C horizontal

875   dotted lines consist in the main limits between the four palynozones discussed in the

876   manuscript. To the left, all radiocarbon dates are represented in Cal BP with rejected dates in

877   italic-grey and selected dates for age model in bold-red.

878

879   **Figure 5:** Nearshore-offshore dinocyst communities plotted in age (Cal years BP) from

880   coastal (A core; Lambert et al., 2019; green code: line or full color), shelf (CBT-CS11 studied

881   core; pink code: line or full color) to full-oceanic (MD95-2002 core; Zumaque et al., 2017;

882   purple full color) waters in the northern Bay of Biscay. Data are expressed in percentages

883   considering all dinocyst taxa for *Lingulodinium machaerophorum* percentages only, and

884   without considering this latter species in the main dinocyst sum for all other taxa percentages.

885   Yellow horizontal band underlines the atypical elevated signatures (percentages,

886   concentrations) of *L. machaerophorum*. A to C horizontal dotted lines consist in the main

887   limits between the four palynozones discussed in the manuscript.

888

889   **Figure 6:** Long-term Holocene insolation trends at 65°N (Berger and Loutre, 1991) in parallel

890   with seasonal Sea-Surface Temperature (SST) and Sea-Surface Salinity (SSS) reconstructions

891   in the north-eastern Atlantic Ocean (MD95-2002 core; Zumaque et al., 2017), as well as

892 qualitative estimates of summer SST South of Iceland (Orme et al., 2018; Eynaud et al.,
893 2018). North Atlantic SubPolar Gyre (SPG) millennial-scale dynamics (density anomalies at
894 sub-thermocline depths recorded in the southern Iceland Basin) are based on temperature and
895 salinity reconstructions of the surface subpolar North Atlantic (Thornalley et al., 2009) and
896 are compared with δ^{18}O signatures of *Cibicides refulgens* and *Ammonia falsobeccarii* benthic
897 foraminifera. δ^{18}O SW (Sea Water) for isotope signatures of Northeast Atlantic water masses
898 (Voelker et al., 2015). ENACW: Eastern North Atlantic Central Waters (P for Polar and T for
899 Tropical). Yellow horizontal band underlines the atypical elevated occurrences of *L.*
900 *machaerophorum* (cf. Figure 5). A to C horizontal dotted lines consist in the main limits
901 between the four palynozones discussed in the manuscript.

902

903 **Figure 7:** Bond Event (BE) curve (Hematite-stained quartz grain percentages; Bond et al.,
904 2001) in parallel with δ^{18}O acquired on *Ammonia falsobeccarii* benthic foraminifera. From
905 mean values of both datasets (i.e. locations of the coloured scale), a code based on
906 positive/negative anomalies has been established in reference with the average of the
907 considered dataset: Red (less Ice-Rafted Debris: IRD or weaker Sup-Polar Gyre: SPG) *versus*
908 blue (more IRD or stronger SPG). Grey horizontal bands underline main common periods of
909 stronger SPG–IRD between both proxies, and blue inserts to the right point to the selected
910 intervals that will be drawn on Figures 8 to 10, especially representative of the *A.*
911 *falsobeccarii* δ^{18}O stronger negative anomalies (Bond events 4, 2 and 1). ENACW: Eastern
912 North Atlantic Central Waters (P for Polar and T for Tropical). A to C horizontal dotted lines
913 consist in the main limits between the four palynozones discussed in the manuscript.

914

915 **Figure 8:** Sedimentological (grain-size analyses and Zr/Al XRF ratio) as well as selected full-
916 oceanic dinocyst data (percentages without *L. machaerophorum* in the main sum, and
917 concentrations) plotted in age for the CBT-CS11 core, in parallel with NGRIP oxygen
918 isotopes (Vinther et al., 2006) to the left as well as Bond events (Bond et al., 2001) and Total
919 Solar Irrandiance (TSI; Steinhilber et al., 2009) to the right of the diagram. Note also
920 additional data from the MD95-2002 slope core (Zumaque et al., 2017): dinocyst-based
921 summer Sea-Surface Temperature (SST) as well as qualitative major occurrences of *O.*
922 *centrocarpum* and *S. mirabilis* (depicted in percentages in Figure 5). Blue horizontal bands
923 are representative of Bond events 4, 2 and 1 from the base to the top of the core. Yellow
924 horizontal band underlines the atypical elevated occurrences of *L. machaerophorum* (cf.

Figure 5). A to C horizontal dotted lines consist in the main limits between the four palynozones discussed in the manuscript.

Figure 9: CBT-CS11 sedimentation rates and selected palynological data (cf. Table 2), in parallel with North Atlantic Oscillation (NAO) data as interpreted from the NAO index (Trouet et al., 2009; Olsen et al., 2012), northern Europe storminess (Goslin et al., 2018; ASI: Aeolian Sand Influx), and winter Sea-Surface Temperature (SST) in the northern Bay of Biscay (Zumaque et al., 2017). Blue horizontal bands are representative of Bond events 4, 2 and 1 from the base to the top of the core. Yellow horizontal band underlines the atypical elevated occurrences of *L. machaerophorum* (cf. Figure 5). A to C horizontal dotted lines consist in the main limits between the four palynozones discussed in the manuscript. IPC: Iberian Poleward Current. NAC: North Atlantic Current.

Figure 10: Selected palynological information from the continent (pollen) and marine (dinocyst) compartments from the CBT-CS11 core exclusively, addressed in parallel with sedimentation rates and Dinocyst *versus* Pollen ratios (cf. Table 2). Blue horizontal bands are representative of Bond events 4, 2 and 1 from the base to the top of the core. Yellow horizontal band underlines the atypical elevated occurrences of *L. machaerophorum* (cf. Figure 5). A to C horizontal dotted lines consist in the main limits between the four palynozones discussed in the manuscript. Cf. Figure 2 for cultural subdivisions in full text.

Figure 11: Synoptic approach of main hydrographic and climatic influences that prevailed at the western French coast scale. Superimposed on the "winter", "autumn" and "winter" modes linked with the long-term insolation trend, millennial and infra-millennial mechanisms imply SubPolar Gyre (SPG) strength coupled or forced by natural atmospheric oscillations such as the North Atlantic Oscillation (NAO) and solar activity. IPC: Iberian Poleward Current; ENACW: Eastern North Atlantic Central Water; NAC: North Atlantic Current; SST: Sea-Surface Temperature.

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a)

Provinces
- Subpolar Gyre (SPG) province
- Arctic province
- Inflow province (NAC)
- Subtropical Gyre (STG) province
- Slope Current province

HAMOC synthesis
red and blue dots on the map
Eynaud et al., 2019
Ayache et al., 2018

Modern SST (°C)
High · 28°C
Median · 13°C
Low · -2°C

SPG
STG
ENACW
SACW
ENACWT

ENACW: Eastern North Atlantic Central Waters Polar
ENACWt: Eastern North Atlantic Central Waters Tropical
NAC: North Atlantic Current
SACW: Southern Atlantic Central Waters

b)

IROISE SEA
CBT-CST
MD95-2002
BAY OF BISCAY
Vilaine estuary
Loire estuary
Gironde estuary
France
Massif Central
Garonne River
Dordogne River
Central Pyrenean mountains
Spain
100 Km

Depth (m)
0 · 250 · 500 · 1000 · 2000 · 3000 · 4000

- Shelf residual circulation
- General oceanic circulation (anticyclonic branch derived from the NAC)
- Slope current = Iberian Poleward Current (IPC) (both from summer and autumn to winter)
- 100 m isobath = winter thermocline (IPC)
- 100 m isobath = winter thermocline horizontal front (freshwater front) separating colder/fresher waters to the east from saltier waters to the west

- Eddies
- Density currents
- Tidal currents
- Wind-induced currents

a) **Depth of core CBT-CS11 (cm)**

b) **CBT-CS11 Age Model**

■ Dated positions
95% Chronology CI

c) **Cultural subdivisions**

Mp: Modern period

M-A2: Late Middle Ages   Middle Ages
M-A1: High Middle Ages
M-A1: Early Middle Ages

R2: Late Antiquity   Roman period
R1: Roman Empire

I2: Second Iron age   Iron age
I1: First Iron age

B3: Late Bronze age   Bronze age
B2: Middle Bronze age
B1: Early Bronze age

N4: Late Neolithic   Neolithic
N3: Recent Neolithic
N2: Middle Neolithic
N1: Early Neolithic

M2: Second Mesolithic   Mesolithic
M1: First Mesolithic

a) Dinocyst dominance index · Dinocyst Margalef index

b) Dinocyst fluxes (cysts/cm²/yr)

— L. machaerophorum (Lmac)
— Total dinocysts without Lmac

% L. machaerophorum (dotted line) · Number of dinocyst taxa (dotted line)

Dinocyst concentrations (cysts/cm³)

c) Pollen dominance index · Pollen Margalef index

d) Total pollen fluxes (pollen/cm²/yr)

% Quercus and Total Trees (dotted line) · Number of pollen taxa (dotted line)

Pollen concentrations (pollen/cm³)

a) Dinocyst assemblages - Core CBT-CS11

b) Pollen assemblages - Core CBT-CS11

Percentages of dinocyst taxa on a proximal-distal gradient : percentages of taxa represented without *L. machaerophorum* counts in the main sum for A and CBT-CS11 cores

Top panel labels (left to right):

L. machaerophorum — Seasonally stratified coastal waters, Summer SST>12°C, Nutrient input, Brackish water

Stratification — Colder coastal water

Mesotrophic to permanently to eutrophic env.

Temporarily or permanently reduced salinities

Coastal productivity

Coastal env. with reduced salinities

Fully marine to coastal temperate species, Oligo- to eutrophic conditions

ESTUARIAN — SHALLOW BAY - INNER NERITIC

Age (ka Cal BP): C, B, A

Bottom panel labels (left to right):

S. ramosus / *I. trifolium* — Cosmopolitan Iroise Sea

O. centrocarpum — Temperate to subpolar N. Atl

S. mirabilis — Env. between subtropical fronts

T. vancampoae — Subtropical to temperate Full oceanic

Selenopemphis spp to the N. Atlantic — between subtropical and Arctic fronts in the North Atlantic

Brigantedinium spp — Upwelled waters

IROISE SEA - NERITIC — OUTER NERITIC to FULL-OCEANIC

Age (ka Cal BP): C, B, A

Total dinocyst conc. without *L. machaerophorum* (10³ cysts.cm⁻³)

L. machaerophorum conc. (10³ cysts.cm⁻³)

Legend:
- Slope, MD95-2002, 2174m water depth
- Shelf, CBT-CS11, 73m water depth
- Bay of Brest, Core A, 8.2 m water depth

Hematite-stained quartz (%) (Bond et al. 2001)
(black solid line)

δ¹⁸O *A. falsobeccarii* (This study)
(black: mobile average on 3 points / grey: all data)

More IRD

Weak SPG

Transition for comparison
with the dotted line

BE 1b

BE 1a

1.2-1.6

BE 2b

Moriya et al. 2014

BE 2a

2.7-3.3

BE 3b

BE 3a

BE 4b

5.1-6.4

BE 4a

* ENACW cooled by 1 +/- 0.7 °C
and densities decreased by 0.4 +/- 0.2

SPG strength code
used as a reference
for Figs 8, 9 and 10

~2.6-3.3 ka Cal BP

Limits for blue bands on Figs 8, 9, 10. Bond events 1, 2 and 4

CBT-CS11 sedimentological and palynological data

« NAO-like » observations

Sedimentation rates (cm/yr)   Riparian pollen grains %   SST-Winter (Zúñiga et al. 2017)   Stranded ASJ (Quinn et al. 2018)

Ratio *O. centrocarpum* (NAC) / %. *I. machaedophorum*   Ratio *Corylus* / Fluxes (palynomorph/cm²/yr)   NAO data (Trouet et al. 2009;
%. *I. machaedophorum* (Loire River)   (*Corylus/Quercus*)   Olsen et al. 2012; black dotted line)

Stabilization of estuarine banks and alluvial forests
More sediments trapped in river systems

Major intervals of higher
Loire flood frequencies

Increased southern   Increased storminess
Subpolar gyre winter SST   Northern Europe (Denmark)
IPC+ (NAO-like)   NAO+ (NAO-like)

A) « Summer prevailing mode » (until 5.9 ka BP)
Overall oceanic influence in the whole Bay of Biscay

EARLY - MIDDLE NEOLITHIC

« Autumn event » (especially 5.9 to 4 ka BP)
Mixed Oceanic-Fluvial influences

RECENT - LATE NEOLITHIC

B) « Winter prevailing mode » (from 3.3 ka BP)
Overall fluvial influence on the shelf

FROM THE BRONZE AGE

Map A labels:
- Higher SUMMER precipitations
- Stronger upwelling
- Spain

Map middle labels:
- Higher WINTER precipitations
- River plumes

Map B labels:
- Europe storminess to the N
- NAO+
- Winter storminess to the S
- NAO-
- Spain

Legend:
- Density currents (winter)
- Wind-induced circulation
- 180 m isobath = winter thermohaline horizontal front (freshwater front)

Depth (m)

Orbitally-driven hydrographic changes

A)
- Shelf residual circulation: Stronger summer NW-SE direction
- Upwelling: Stronger
- Slope current: less intense IPC influence to the southern and central Bay of Biscay

B)
- Shelf residual circulation: Stronger SE-NW direction
- Upwelling: Reduced
- Slope current: more intense IPC influence to the southern and central Bay of Biscay

Oceanic-driven millennial climate changes (superimposed on A) or B) : example with strong SPG on B) / example with strong IPC influence on A)

Strengthened Subpolar Gyre :
- Increased ENSO-like activity (...)
- Intensified northward heat transport through the NAC
- Increased SST South of Iceland (Irminger Current)
- Northern European storminess (Daobis et al., 2018)
NAO+ prevalent configuration

Weakened Subpolar Gyre :
- Decreased ENSO-like activity (...)
- Decreased North Atlantic oceanic influence through NAC
- Via NAC connection to the IPC
- Increased warm SST in the NE Atlantic Ocean : stronger IPC (MO80-2002)
- Decreased SST South of Iceland (Ortiz et al, 2016 and others)
NAO- prevalent configuration

Code	Depth (cm)	Sample nature	Age 14C BP	Error	Age min (<u>mean</u>) max Cal BP
SacA41576	*0**	*Turritella communis*	720	30	457(**481**)505
SacA 32019	*29**	Bivalve	715	35	451(**477.5**)504
SacA 32020	50	*Turritella communis*	645	30	305(**386.5**)468
Poz-71200	*79**	*Turritella communis*	820	30	501(**525**)549
SacA 32021	91	*Turritella communis*	1340	30	923(**940.5**)958
SacA38446	101	Bivalve	1505	30	1049(**1115**)1181
SacA39684	120	*Turritella communis*	1765	30	1297(**1339.5**)1382
SacA39683	151	*Turritella communis*	2180	35	1713(**1793**)1873
SacA 32022	165	*Turritella communis*	2600	30	2307(**2326.5**)2346
SacA38447	170	*Turritella communis*	2750	30	2360(**2424.5**)2489
SacA 32023	187	*Turritella communis*	3080	30	2777(**2851.5**)2926
SacA55615	**200**	Bivalve	3410	30	3219(**3294.5**)3370
SacA 32024	*203**	*Dentalium*	3695	30	3560(**3627**)3694
SacA55616	**210**	*Turritella communis*	3895	30	3834(**3869**)3904
Poz-71201	220	*Turritella communis*	3875	35	3720(**3823**)3926
SacA39682	*220 **	*Turritella communis*	3425	35	3218(**3301.5**)3385
SacA55617	**234**	Bivalve	4265	30	4288(**4366.5**)4445
SacA55618	**244**	Bivalve	4450	30	4565(**4646**)4727
SacA39681	*250**	*Turritella communis*	4940	35	5345(**5405**)5465
SacA39680	278	*Turritella communis*	5205	35	5583(**5622.5**)5662
SacA 32025	315	*Turritella communis*	5650	30	5997(**6096**)6195
SacA38448	316	*Turritella communis*	5630	30	5995(**6089**)6183
SacA 32026	360	Bivalve	6200	30	6667(**6698**)6729
SacA 32027	376	*Turritella communis*	6415	30	6910(**6952**)6994
SacA38449	385	*Turritella communis*	6480	30	6967(**7064**)7161

Table 1

CBT-CS11 data	Figures with data (D for Dinocyst and P for Pollen)	Methodology and/or Interpretation of the signal
Radiocarbon dates	Table 1, Figure 1a	Calibration with the Calib 7.1 software using the calibration curve IntCal13 (Stuiver and Reimer, 1993; Reimer et al., 2013), with a reservoir age of -324 years (Mangerud et al., 2006)
Age model	Figure2b	Bchron package under the R program version 3.5.1
Palynomorph concentrations Pollen (P) – Dinocysts (D)	Figures 3b (D), 3d (P), 5 (D)	Marker grain method with *Lycopodium* spores (de Vernal et al., 1999; Mertens et al., 2009): calibrated tablets of known numbers of *Lycopodium* spores are added to each sample before chemical treatments (Stockmarr, 1971)
Palynomorph fluxes	Figures 3b (D), 3d (P), 9 (P and D)	Multiplication of concentrations (taxa/cm³) by sedimentation rates (cm/kyr), fluxes expressed in taxa/cm²/kyr
Dominance index	Figures 3a (D), 3c (P)	Dominance ranges from 0 (all taxa are equally present) to 1 (one taxon dominates the community completely)
Diversity (Margalef) index	Figures 3a (D), 3c (P)	Number of taxa per sample (S) and Margalef's richness index: $(S – 1)/\ln(n)$, where n is the number of individuals counted in each sample
Major pollen taxa in assemblages	Figure 4b	Pollen percentages are calculated using a main sum excluding *Pinus*, spores, and indeterminable pollen grains
Major dinocyst taxa in assemblages	Figures 4a (in depth), 5 (in age)	Dinocyst assemblages are described by the percentages of each species calculated on the basis of the total dinocyst sum including unidentified taxa and excluding pre-Quaternary specimens.
Sum *O. centrocarpum* and *S. elongatus*	Figure 8	Grouping of "North Atlantic subpolar gyre influence" taxa according to Detrended Correspondence Analysis analysis performed on dinocyst communities and other environmental variables (Data in Brief). Percentages calculated without Lmac in the main cyst sum.
Ratio *O. centrocarpum* over *L. machaerophorum*	Figure 9	Ratio between North Atlantic Current (NAC) tracer and estuarine (Loire) tracer so as to discuss oceanic *versus* continental influences at the mid-shelf core location
Ratio *Corylus* over *Quercus*	Figure 9	As trees in general suffer deforestation in parallel with the increase in Poaceae, the ratio *Corylus* over *Quercus* makes it possible to highlight the more pronounced/rapid decline of the corylaie
Ratio Dinocyst / Pollen	Figure 10	Marine versus strict continental tracer allowing to address the influence of both compartments (aquatic and terrestrial realms) in the fine sediment deposits of the mid-shelf
Sum *S. quanta* and *Echinidinium* spp.	Figure 10	Grouping of "Coastal heterotrophic" taxa according to Detrended Correspondence Analysis analysis performed on dinocyst communities and other environmental variables (Data in Brief). Percentages calculated without Lmac in the main cyst sum.

δ^{13}C and δ^{18}O (‰VPDB) *A. falsobeccarii*	Figures 6, 7	Foraminifera cleaned in a methanol ultrasonic bath for a few seconds, then roasted under vacuum at 380°C for 45 min to remove organic matter. Measurements at the IRMS platform: MAT253 mass spectrometer coupled with a KIEL IV preparation line for benthic species (PSO, Plouzané)
δ^{13}C and δ^{18}O (‰VPDB) *C. refulgens*	Figure 6	Mojtahid et al., 2019. Measurements on the GasBenchII platform (PSO, Plouzané)
D50 CaCO$_3$-free grain-size	Figure 8	Mojtahid et al., 2019. Sediment decarbonatation with 1 M hydrochloric acid. Laser diffraction particle size analyzer (Malvern™ Mastersizer 3000; LPG-BIAF, Angers)
XRF data : Log (Zr/Al)	Figure 8	Proxy for coarser sediments quartz-sand according to Canonical Correspondence Analysis conducted on XRF data

Table 2