Changes in Holocene meridional circulation and poleward Atlantic flow: the Bay of Biscay as a nodal point

Mary, Yannick (1), Eynaud, Frédérique (1), Colin, Christophe (2), Rossignol, Linda (1), Brocheray, Sandra (1, 3), Mojtahid, Meryem (4), Garcia, Jennifer (4), Peral, Marion, (1, 5), Howa, Hélène (4), Zaragosi, Sébastien (1), Cremer, Michel (1)

(1) Laboratoire Environnements et Paléoenvironnements Océaniques et Continentaux (EPOC) -UMR 5805, Université de Bordeaux, 33615 Pessac, France
(2) Laboratoire Géosciences - Université de Paris-Sud, 91405 Orsay Cedex, France
(3) now at: Institut Polytechnique LaSalle-Beauvais – Dpt Géosciences, 19 rue Pierre Waguet – BP 30313 – 60026 Beauvais, France
(4) UMR CNRS6112 LPG-BIAF, Recent and Fossil Bio-Indicators, Angers University, 2 Bd Lavoisier, 49045 Angers CEDEX 01, France
(5) now at Laboratoire des Sciences du Climat et de l'Environnement (LSCE-IPSL), Domaine du CNRS, bât.12 - 91198 Gif-sur-Yvette, France

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Abstract

This paper documents the last 10 ka evolution of one of the key parameters of climate: sea-surface temperatures (SST) in the North Atlantic. We focus on the southern Bay of Biscay, a highly sensitive oceanographic area regarding the dynamics of the North Atlantic subpolar and subtropical gyres (SPG and STG respectively). This site furthermore offers unique sedimentary environments characterized by exceptional accumulation rates, enabling the study of Holocene archives at (infra)centennial scales. Our results mainly derive from planktonic foraminiferal association analysis on two cores from the southern Landes plateau. These associations are used as the basis of Modern Analogue Technique transfer functions to track past hydrographical changes. SST reconstructions were thus obtained at an exceptional resolution and compared to a compilation of Holocene records from the north-eastern North Atlantic. From this regional perspective are shown fundamental timing differences between the gyre dynamics, nuancing classical views of a simple meridional overturning cell. Our study highlights that western Europe underwent significant oscillations of (annual) SST during the last 10 ka. During well know intervals of mild boreal climate, warm shifts of more than 3°C per centuries are accurately concomitant

with positive sea-surface temperature anomalies and rise of micropaleontological indicators of gyre dynamics in the northern North Atlantic, pointing to periods of greater intensity of the North Atlantic Current (SPG cell especially) . Conversely, SST signal records short-term cold anomalies which could be related to weaker SPG dynamics.

1. Introduction

The Atlantic Meridional Overturning Circulation (AMOC) and its dynamics are critical regarding the modulations of climate (amplitude and frequency) over Europe (westerlies, droughts and/or stormy periods, e.g. Clark et al., 2002; Bryden et al., 2005; Dawson et al., 2004; Magny et al., 2003; Sorrel et al., 2009; Trouet et al., 2012, Van Vliet-Lanoe et al., 2014a and b, Jackson et al., 2015). The two connected North Atlantic gyres, the subpolar gyre (SPG) and the subtropical gyre (STG) are fundamental for these processes as they transfer heat and salt toward the Nordic seas (e.g., McCartney and Mauritzen, 2001; Perez-Brunius et al., 2004; Hatun et al., 2005; Morley et al., 2014) where convection occurs (e.g. Lozier and Stewart, 2008). Their expansions and contractions notably control the inflow from the North Atlantic Current (NAC) to higher latitudes, thus also affecting the heat budget of the Greenland-Iceland-Norwegian seas, which is critical in the meridional climatic balance (i.e., Hatun et al., 2005). During the late Holocene, changes in the STG and SPG dynamics contributed to well-known climatic anomalies in Western Europe, such as the Little Ice Age or the Medieval Warm Period/Anomaly, and probably played a major role at longer time scales (Thornalley et al., 2009; Colin et al., 2010; Copard et al., 2012; Sorrel et al., 2012; Staines-Urias et al., 2013; Morley et al., 2014;).

By providing the first Holocene inventory of (infra)centennial hydrographic changes in the inner Bay of Biscay, this paper aims at testing European temperate oceanic signals *vs.* those from a broader North Atlantic view with a focus on the SPG dynamics. Our study site (Figure 1) is ideally located under the temperate eastern limb of the NAC, in the southern Bay of Biscay and not far from the STG/SPG divergence zone (e.g. Planque et al., 2003). This geographic configuration provides to this marine environment a high sensitivity regarding Northern hemisphere climatic signals at present (e.g. Le Cann and Serpette, 2009; Esnaola et al., 2012; Garcia-Soto and Pingree, 2012), echoing pan-Atlantic hydrographical changes, somewhat with amplified responses. Actually, the southern Bay of Biscay records at present the warmest SST (especially in summer) of the mid-latitude temperate band of the North Atlantic with a significant warming trend over the last decades (e.g. Koutsikopoulos et al., 1998; Valencia et al., 2003; deCastro et al., 2009, see also maps at http://www.nodc.noaa.gov/cgi-bin/OC5/woa13fv2/woa13fv2.pl?parameter=t). Previous works done on sedimentary archives in the same area have furthermore evidenced a strong potential to track down the Holocene variability (Mojtahid et al., 2013; Garcia et al., 2013; Brocheray et al., 2014; Mary et al., 2015).

Today, the Bay of Biscay is characterized by a complex, variable sea-surface circulation with strong seasonal changes, marked by a September-October versus March-April - *SOMA* pattern (e.g., Pingree and Lecann, 1990; Pingree and Garcia-Soto, 2014). The main surface current in the Bay of Biscay is the European Slope Current (ESC), flowing northward along the Armorican Shelf (Figure 1), with important spatial and seasonal variations (Garcia-Soto and Pingree, 2012; Charria et al., 2013). Circulation can reverse during summer along the shelf break, flowing weakly southwestward (Charria et al., 2013). In autumn-winter, the northward flow reaches a maximum, especially when combining with southern intrusions from the Iberian Poleward Current (IPC) which flows along the western Iberian margin (e.g. Peliz et al., 2005) before turning eastward at the Cape Finisterre (NW Spain). The IPC northward extension into the Bay of Biscay is known as the Navidad Current (e.g. Garcia-Soto et al., 2002; Le Cann and Serpette, 2009). The winter mixing of the IPC and ESC is designated as the European Poleward Current (EPC, Garcia-Soto and Pingree, 2012), and drives relatively warm and saline water to the Nordic seas, contributing to their heat and salt budget. The Bay of Biscay is additionally strongly marked by surface water inflow coming from the North Atlantic Current (Figure 1), which enters the Bay from its northwestern boundary (Pingree, 2005; Pingree and Garcia-Soto, 2014; Ollitrault and Colin de Verdiere, 2014). In contrast with surface circulation of the inner Bay of Biscay, the NAC water inflow shows only limited seasonal variability. At inter-annual time scales however, NAC oscillations are mainly driven by westerly wind regime (Pingree, 2005), and consequently by the North Atlantic Oscillation (NAO), one of the key modes of climatic variabilityin the North Atlantic. So far, little is known about long term oscillations of the NAC inflow into the Bay. Modern surveys of SST variability over the last 150 years in the Bay of Biscay report that temperature oscillations are mainly controlled by the Atlantic Multi-decadal Oscillation (AMO, Garcia-Soto and Pingree, 2012). The influence of the NAO on SST in the Bay of Biscay is more complex and contributes only little to the observed long term trend, although sharp, inter-annual changes of the NAO index impact annual SST variability (Garcia-Soto and Pingree, 2012, Figure 1C). Moreover, NAO conditions influence large-scale oceanic circulation patterns indirectly responsible for surface temperature anomalies over the Bay (Pingree, 2005; Garcia-Soto and Pingree, 2012, see also the synthesis within Mary et al., 2015).

The present paper is based on analyses conducted on two high-resolution well dated cores from the southern part of the inner Bay of Biscay (Figure 1, Table 1): core KS10b (e.g. Mojtahid et al., 2013) and core PP10-07 (e.g. Brocheray et al., 2014). These cores show exceptionally high sedimentation rates for the Holocene, up to 200 $cm.ka^{-1}$ for core PP10-07, and 86 $cm\ ka^{-1}$ for core KS10b (see detailed description of these archives and of their sedimentological context in the respective references). Here we present past Holocene SST data reconstructed after an ecological transfer function based on the Modern Analogue Technique (see Methods) applied to planktonic foraminiferal assemblages. These Bay of Biscay sea-surface reconstructions are compared to selected North Atlantic Holocene records using a data mining exercise (referencing sea-surface reconstructions of high time-resolution) done in the frame of the French ANR HAMOC (Holocene North Atlantic Gyres and Mediterranean Overturning dynamic through Climate Changes) project database (see http://hamoc-interne.epoc.u-bordeaux1.fr/doku.php?id=start) .

2. Methods

2.1. Age models

Updated age models have been built for the Bay of Biscay cores. All raw ^{14}C ages were calibrated and converted to calendar ages using the Marine13 calibration curve and the recommended age reservoir of 405 years (Reimer et al., 2013), as no adequate and robust local age reservoir values exist in the area (see Mary et al., 2015 for a discussion). Smooth-spline regression based on the published ^{14}C dates (n =12 for core Ks10b, Mojtahid et al., 2013) were applied (Figure 2). For core PP10-07, two supplementary ^{14}C dates were obtained at the top of the sequence (Table 2) and the age model was built using a 5 degree polynomial regression (Figure 2). Core MD03-2693 age model (also exploited in this paper) was built using linear interpolation based on published ^{14}C and ^{210}Pb (n=3 and n=8, respectively, Mary et al., 2015). Age-depth modeling and calibration were performed using the dedicated software Clam (Blaauw, 2010), written in the open-source statistical environment R (http://www.r-project.org/).

2.2. Past hydrographical parameter quantification

Planktonic foraminifera (PF) assemblages were used to quantify sea-surface parameters: species abundances were determined (counts of 300 specimens at least) on the > 150 µm fraction from sedimentary aliquots retrieved at maximum 10 centimeter-intervals along the studied cores, thus giving a mean time resolution of 50 and 150 years for core PP10-07 and KS10b respectively (see Supplementary material for detailed data). SST reconstructions were calculated using the Modern analogue technique (MAT) a method successfully developed on PF (e.g., Pflaumann et al., 1996; Kucera et al., 2005; Telford and Birks, 2011; Guiot and de Vernal, 2007; 2011). The calculations derive from modern spectra previously compiled and tested separately in the frame of the MARGO exercise for the North Atlantic Ocean and the Mediterranean Sea respectively (Kucera et al., 2005; Hayes et al., 2005). They are based on sediment surface samples analyzed for their contents in PF (specific relative abundances) and thus offer the advantage of already having integrated regional taphonomic processes. At EPOC (Environnements et Paléoenvironnements Océaniques et Continentaux) laboratory, these two MARGO databases were summed to provide larger analogue choices and ambiguous data points were excluded (i.e. non-stratigraphically constrained points showing anomalies in the biogeographical distribution), resulting in a final training set of n=1007 modern analogues. Modern sea-surface parameters were extracted from the WOA ATLAS with the sample tool developed by Schäfer-Neth and Manschke (2002). The latter was developed for the MARGO program and interpolates the 10 m World Ocean Atlas WOA -1998 mean seasonal and mean annual temperatures over the four existing data points surrounding the sample location (see http://www.geo.uni-bremen.de/geomod/staff/csn/woasample.html) thus providing spatio-temporal averaged values of SST (see Kucera et al., 2005 for MARGO analytical developments and Telford et al., 2013 for further considerations).

Calculations were run under the R software with the BIOINDIC package (ReconstMAT script) developed by J. Guiot (https://www.eccorev.fr/ spip.php?article389) using relative abundances of PF with no mathematical transformation (no logarithmic or square root transformations which are frequently used to increase the equitability within assemblages for instance, see Guiot and de Vernal, 2007 for a review). Past hydrological parameter values are derived from a weighted average of the SST values of the five best analogues. The maximum weight is given for the closest analogue in terms of statistical distance (i.e. dissimilarity minimum). The ReconstMAT script furthermore includes the calculation of a threshold regarding this statistical distance which prevents calculation in the case of poor- or non- analogous situations. The degree of confidence of this method allows reconstruction of seasonal and annual SST with a maximum root mean square error of prediction (RMSEP) of 1.3°C (see Supplementary material). This method (named MATR_1007PF for Modern Analogue Technique derived from 1007 modern spectra of PF assemblages) was extensively tested at EPOC including comparisons with similar MAT developed regionally on PF (e.g. Salgueiro et al., 2008; 2010) providing very coherent reconstructions along the western European margin (see Eynaud et al., 2013 for further details) and producing pertinent paleoceanographical series (see Penaud et al., 2011; Sánchez Goñi et al., 2012; Sánchez Goñi et al., 2013 for records also produced with MATR_1007PF). Additionally, our work benefited from modern calibrations conducted on PF from the same area of the Bay of Biscay (i.e. Retailleau et al., 2009; 2012).

3. Holocene SST oscillations in the Bay of Biscay

Despite the different bathymetric and physiographic positions of the studied cores (Figure 1, Table 1), reconstructed annual SST in the Bay of Biscay show coherent oscillations of remarkably similar timing (Figure 3a). Small amplitude differences are observed between the two studied records, but synchronous warm periods are clearly identified between 8.2-7.4 ka BP and 6.6-5.6 ka BP, these intervals roughly corresponding to the upper and lower limits of the mid-Holocene hypsithermal in the North Atlantic region (e.g. Eynaud et al., 2004; Walker et al., 2012; Tanner et al., 2015).

On historical time-scales, warm intervals are detected in both cores between 2.6-1.8 ka BP (Roman Warm Period, RWP) and 1.2-0.5 ka BP (Medieval Warm Period, MWP), although less obvious in core KS10b because of the lower time resolution. An offset of up to 4°C above mean annual modern values is observed during a large temperature excursion around ca 2 Ka BP in core PP10-07 only. The amplitude of the warmings detected between 8.2-7.4 ka BP and 6.6-5.6 ka BP reaches 2 to 3°C in both records. Such amplitudes in the detected SST warm pulses are especially high in comparison to modern annual values. However, considering the strong modern seasonal SST variations in the Bay of Biscay (as shown on Figure 3a), a 4°C shift of mean annual SST is coherent with a deviation of annual mean temperature toward mean summer values.

Comparison of the southern Bay of Biscay SST reconstructions with other records from the Western European margin (Figure 3, 4 and 5) suggests that the observed millennial-scaled warm episodes are coherent features which reflect characteristic climatic patterns, at least expressed regionally, but also probably more broadly. Indeed, further along the Bay of Biscay margin, other high resolution Holocene archives reveal similar and synchronous episodes (Figure 3C). Concomitantly to the observed warm SST pulses also seen within the seasonal means (see Supplementary material), Holocene pollen assemblages from core VK03-58 bis (pollen data not shown, Naughton et al., 2007a) indicate a decrease in mean annual precipitations; this drought being related, according to the authors, to a change in the seasonality with warmer summers especially. In the same way, the evolution of coccolithophorid concentrations in the subpolar North-Atlantic along the Irminger Current pathway, interpreted as indicating stronger contribution of NAC water toward the Nordic seas (Andrews and Giraudeau, 2003; Giraudeau et al., 2004, Moros et al., 2012), showed strong similarities with the Bay of Biscay SST signals. Peaks in coccolithophorid abundances in cores B997-330 and MD99-2269 (Figure 4e and f) (see location on Figure 1) were recorded synchronously to the warm pulses in the Bay of Biscay, with especially positively marked anomalies detected around 2 ka BP and 8 ka BP. The Bay of Biscay SST oscillations further correspond with those reconstructed from marine records from the Barents Shelf (see location on Figure 1) from core MSM5/5-712-2 (Werner et al., 2013, Figure 3c) and core M23258 (Sarnthein et al., 2003; Figure 3d). This coherency suggests teleconnections between the southern Bay of Biscay and the Nordic seas, probably due to a common driving mechanism linked to the NAC inflow vigor and its split between the SPG and the STG.

In between the observed warm intervals, SST reconstructions of core PP10-07 and KS10b reveal several low values slightly colder than today (Figure 3a). The time interval between 5.6 and 2.6 ka BP is characterized by temperatures around -1°C cooler compared to the modern ones. This period roughly corresponds to the late Holocene Neoglacial Cooling (e.g. Eynaud et al., 2004; Wanner et al., 2008; Walker et al., 2012). In the same way, short-lived events of 2°C cooling are visible around ca 8.2, 7, 5.5, 4, 2.9 and 1.7 ka BP (Figure 3 and 4). The three older anomalies are synchronous and well-marked in both KS10b and PP10-07 cores.

The comparison of the timing of these cold spells to other existing Holocene reconstructions from the North Atlantic Ocean reveals that they represent coherent and reproducible features (Figure 4). Interestingly, density anomalies thought to reflect millennial-scale variability in the SPG dynamics (Thornalley et al., 2009; Farmer et al., 2011) were recorded nearly synchronously (within the age model uncertainties) in the southern Iceland basin (it is especially obvious before 4ka). These anomalies were interpreted (i.e. Thornalley et al., 2009) as reflecting a strong /*weak*, longitudinally extended/*contracted* SPG thus driving more/*less* vigorous but fresher/*saltier* Atlantic inflow throughout the Faroe current branch and thus modulating the AMOC strength. The good temporal correspondence between the cold spells detected in core PP10-07 (even if shorter) and the density anomalies (core RAPiD-12-1K, Figure 4h) registered in the subpolar North-Atlantic support, as seen for warm events, a direct teleconnection with the inner Bay of Biscay, probably throughout a STG/SPG seesaw which would influence tracks/intensities of the temperate westerlies. The short lived cold anomalies of PP10-07 are furthermore concomitant with periods of increased storminess identified in various coastal sediments from the NW European margin (Holocene Storm Periods after Sorrel et al., 2012, Figure 3g). These periods have been related to a weakened, westward contracted SPG, involving a rapid feedback in the atmospheric dynamics (e. g. westerlies intensity and/or latitudinal migrations).

In the subtropical North Atlantic, study of benthic foraminiferal stable isotopes in core EUGC-3B (located in the Galician Shelf, Pena et al., 2010; see Figure 1) also showed similar cold anomalies which were interpreted by the authors as suggesting enhanced contribution of colder, NE Atlantic ENACW waters reaching the Iberian margin during these events.

4. The European poleward current and the influence of subtropical sourced waters in the Bay of Biscay

Modern surveys (e.g. Garcia-Soto et al., 2002; Lozier and Stewart, 2008; Garcia-Soto and Pingree, 2012) and paleoceanographic time-series (e.g., Mojtahid et al., 2013) recently evidenced the influence of the IPC, and its extension in the Bay of Biscay (i.e. Navidad Current, Garcia-Soto et al., 2002), on surface circulation and hydrological conditions along the European Margin. At present, these incursions of warm waters in the bay occur during winter under specific seasonal wind regimes (of southerly wind off Portugal and westerly wind off Northern Spain, Charria et al., 2013) and negative anomalies of sea level pressure over the North Atlantic (Pingree and Garcia-Soto, 2014). While these conditions were previously related to a negative mode of the NAO (Garcia-Soto et al., 2002), recent analysis of instrumental time-series showed that weather conditions responsible for Navidad current may not always correspond to a fixed value of the NAO index (Pingree and Garcia-Soto, 2014). The Navidad Current occasionally creates warm SST anomalies, enhanced transport of warm water through the pole and could thus be the vector of planktonic exotic (from subtropical origin) faunal invasions in the inner Bay of Biscay (see Mojtahid et al., 2013 and Garcia et al., 2013 for example in the fossil record; see Garcia-Soto and Pingree, 2012 and Pingree and Garcia-Soto, 2014 for example in instrumental time-series) which could bias our SST reconstructions. In the following, we thus examine the hypothesis of a persistent poleward surface current during the Holocene that would have triggered the observed SST warm anomalies in the PP10-07 and KS10b records.

In order to test the coherency of surface hydrographic features along the temperate and subtropical adjacent portions of the European margin, we compared Bay of Biscay SST reconstructions with existing SST (annual) records produced along the Iberian Margin (Figure 3b and c). We first test this link over historical times, compiling SST high resolution data obtained on the proximal core MD03-2693 (after Mary et al., 2015), which accurately complete those from core PP10-07 (see Figure 3a between 0.5 and 1.5 ka and Figure 5a’, even if the cores are not tuned on each other’s, i.e. keeping their independent age models; see also - AC2: 'Author Comment to Ref#2', Frederique Eynaud, 08 Dec 2016 and its cp-2016-32-supplement), with additional high resolution records (Figure 3b). The combination of these records reveals a slight warming associated to the Medieval Warm Period and coherent low-amplitude multi-decadal SST oscillations which echoes those of AMO anomalies as reconstructed by Mann et al (2009). Especially striking is the high degree of synchronicity detected between the Iberian margin (core PO287-06 , Abrantes et al., 2011) and the Bay of Biscay at the scale of the last 1.5 ka, despite differences in the proxies used to generate paleo-SST (Alkenones vs MAT on PF respectively) and age-model uncertainties (which probably explain offsets of a few hundred years around 1200 A.D.). The good coherency with AMO reconstructions further supports modern oceanographic assumptions of AMO driving multi-decadal change of SST in the area (Garcia-Soto and Pingree, 2012) and shows that this modulation is at least valid for the late Holocene. Interestingly, modern winter incursions of Iberian water through the Bay of Biscay take place during periods of increasing AMO (Garcia-Soto and Pingree, 2012). During these episodes, warm winter anomalies of up to 1.1°C are observed in the Bay of Biscay, which are consistent with the amplitude of the warmings detected in both MD03-2693 and PP10-07 past reconstructions.

However, over the longer Holocene perspective, existing SST records from the Iberian margin do not reveal any coherent patterns with those from the Bay of Biscay over the last 10 ka (Figure 3c). Regardless of the proxies involved in SST reconstructions (Alkenones and MAT), there is no evidence of any earlier distinct SST excursions in the high time resolution data of the Iberian cores MD99-2331, D13882, MD95-2042 and MD01-2444 (Figure 3c, see also Figure E4 in the Supplementary material) or elsewhere in other lower resolution Holocene records from the same area (Naughton et al., 2007b; Martrat et al., 2007; Rodrigues et al., 2009; Voelker and de Abreu, 2011; Chabaud et al., 2014). The early Holocene SST reconstructions in this area show a monotonous long term decrease of SST correlated with the Holocene decline of summer insolation (e.g. Marchal et al., 2002, see also Figure E4) which contrasts strongly with the warm episodes observed in core PP10-07 and KS10b at that time (see Figure E4 in the Supplementary material). Taking into account the similarities between late Holocene records in the Iberian margin and in the Bay of Biscay, our data thus suggests a disconnection between these two regions during the first part of the Holocene, up to 1.5 ka BP. We interpret this divergence as a distinct response of the Bay of Biscay to North Atlantic millennial changes in the NAC/SPF system dynamics (e.g. Perez-Brunius et al., 2004) whereas southwestern Europe has probably undergone a mixed influence of diverse subtropical climatic trends. Sea-surface environments from the Bay of Biscay, located at the interface between the SPG and STG influences may have, as currently observed in frontal regions, recorded an amplified signature of NAC shifts, themselves driven by contraction/extension phases of the whole North-Atlantic gyre system (STP, SPG, and Polar Gyre also). To decipher the role of each of these gyres is at present not possible on the basis of our records only, and requires additional high-resolution comparable marine archives along a latitudinal gradient at least between 30° and 60°N. The analyses of the influence of Mediterranean hydrographic changes (via the Mediterranean outflow export especially) together with those linked to the Eastern North Atlantic Upwelling Region would also be very important to tackle in such a context.

5. Implication for Holocene climate dynamics

In agreement with modern climate observations (e.g. Ba et al., 2014), North Atlantic paleoceanographic studies describe a strong impact of the Subpolar gyre (SPG) dynamics on the NAC inflow toward high-latitudes and global circulation during the Holocene (Bianchi and Mc Cave, 1999; Oppo et al., 2003; Perez-Brunius et al., 2004; Thornalley et al., 2009; Giraudeau et al., 2010; Moros et al., 2012; Staines-Urías, 2013; Morley et al., 2014). Freshwater fluxes in the Labrador Sea and wind stress over the North Atlantic are key drivers of eastern expansions/contractions of the SPG (Hatun et al., 2005), thus also controlling the salinity balance over the North Atlantic, boreal deep-water convection and North hemisphere climate patterns. The compilation of proxy-records from further south in the Bay of Biscay indicates that the Holocene relatively long-term periods of warming are interbedded/superposed to rapid, millennial cold anomalies of SPG origin (Figure 4). In agreement with other North Atlantic records, strong NAC occurs preferentially during the Holocene optimum (Berner et al., 2007; Solignac et al., 2008), and during the Roman Warm Period (Werner et al., 2012). In contrast, the occurrences of cold anomalies in the North Atlantic follow a 1500 years periodicity during the Holocene (e.g., Thornalley et al., 2009; Debret et al., 2007; Sorrel et al., 2012), and are accurately reflected by the SST PP10-07 record (Figure 4f).

As also suggested by recent studies of modern time-series (Lozier et al., 2010; Lozier, 2012), Holocene SST records from the Bay of Biscay evidence a decoupling of gyre dynamics, and a potential gyre-specific expression of the AMOC. Model studies similarly question the meridional coherence of the AMOC, revealing an inherent character of its mid-latitude variability at decadal time-scales (Bingham et al., 2007), mainly driven by wind forcing and eddy variability. While our findings support coherent sea-surface hydrographical patterns between subtropical and temperate environments along the western European margin, suggesting a coupled SPG/STG gyre dynamics over the last 1.5 to 2 ka, earlier Holocene contexts seem to have been rather favorable to a gyre-specific expression, i.e. each gyre being related to intrinsic forcing mainly due to their latitudinal position and to proximal saline/fresh water intrusions.

To tentatively go further in the interpretations, we have compiled bibliographic sources dealing with the Holocene climatic variability. Many of the relevant records are considered on Figures 4 and 5, with a zoomed representation over the last 4 ka in Figure 5(5a' to 5e') which gathers proximal European records. Related interpretations and elements regarding the SPG/STG (and other ocean and climate features when existing) were also compiled as a Table (see Table E2 in Supplementary material) to provide a comprehensive summary which is conceptualized on Figure 6. With this exercise, is confirmed that no definitive trend could be assessed over the whole Holocene. It seems rather that the delimitation of the mid-Holocene is of high relevance regarding the latitudinal coherence of climatic events. Probably in relation with the influence of relict ice-sheet melting (and thus fresh-water injection in the SPG) and the related sea-level rise stop, key connections and feedbacks may have took place after 6/5 ka only, thus triggering modern oceanographic and climatic modes. Actually, when focusing on the early Holocene, warm anomalies in the Bay of Biscay coincide with signals of significant NAC inflow in the GIN seas (Figures 4 and 6a), but are not clearly seen on records close from European ice-sheets (Figure 5e). At a millennial scale, these events seem to be in phase with evidences of solar activity changes (Figure 5f – reverted scale) and important pulses of ice-drifting in the North Atlantic (after Bond et al., 2001, Figure 5g). The centennial evolution within each event is however more complex. Over the last 5 ka, trends seem to be more clearly expressed with, especially during the last millennia, good coherency at the local and regional scales (Figure 5a' to 5e'). Warm/cold shifts occur in a well-defined temporal frame, relevant at least over Europe, but hardly attributable on the basis of our work to a preferential radiative forcing (internal as external).

To understand climatic processes behind these observations and test their coherency region per region, a pan-(North)-Atlantic view is however required, emphasizing the need for comprehensive data compilation efforts as those undertaken for instance in the work conducted for the Ocean2k SST synthesis (e.g. McGregor et al., 2015) or the PAGES 2K Network consortium (http://pastglobalchanges.org/ini/wg/2k-network/intro). SST records should however be supplemented by complementary parameters when possible, especially to document hydrographic processes at various depths, in order to better understand the 3D articulation of the oceanic thermal and dynamic responses to various Holocene forcing (e.g. changes in insolation, sea-level - gateway connection, volcanism, or even anthropogenic related, which could have been cumulative or not).

6. Conclusion

Our study, which documents Holocene surface hydrographical changes at unprecedented time-scales in the Bay of Biscay, reveals contrasted patterns (warm *vs* cool SST) which correlate with other North Atlantic proxy records interpreted to be responding to North Atlantic gyre dynamics. Coherently with stronger NAC inflow in the Nordics seas as detected in other archives from the northern North Atlantic, our high-resolution sedimentary records identify specific warm periods during the early Holocene and at ca. 2 ka BP and reveal that northward advection of subtropical waters may have influenced SST oscillations in the Bay of Biscay during the last 1.5 ka BP. In addition, SST signals from the Bay of Biscay show the occurrences of short-term cold anomalies, interpreted here as the signature of changes in SPG dynamics. The influence of the two main North Atlantic gyres, i.e STP vs SPG, observed asynchronously over most of the Holocene in the Bay of Biscay, indicate fundamental differences in the temporal variability of their dynamics, contrasting with the idea of a coherent, basin-wide-driven, overturning cell in the North-Atlantic. Our results suggest a gyre-specific expression of the AMOC where intrinsic salinity valves, linked to the latitudinal and geographical contexts, are of major importance. That may contribute to strong regionalisms in the response of the North Atlantic hydrography to Holocene climatic changes and imply to be as precise as possible when modeling this key component in the Earth climate system. This urges also for a densification (and maybe diversification) in the coverage of past Holocene archives.

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M.Y. and E.F. designed the study and wrote the paper in the frame of the ANR HAMOC project coordinated by C.C..
E.F., R.L., M.M., G.J., P.M., H.H. performed and/ or supervised planktonic foraminifera assemblage analyses and picking for the datings. E.F. ran the transfer function. M.Y. performed age modelling with the help of E.F. and M.M.. B.S, S.Z. and C.M. investigated the sedimentology of core PP10-07. All authors contributed to discussions and interpretation of the results. The authors declare no competing financial interests.

8. References

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Table caption

Table 1: Location and references of the southern Bay of Biscay cores used in this study.

Table 2: Summary of AMS ^{14}C ages of core PP10-07 with calendar correspondences.

Cruise, Core label	*Latitude (°N)*	*Longitude (°E)*	*Water depth (m)*	*Longitudinal distance (km) from the shore*	*Datasources and references*
SARGASS, PP10-07	43.677	-2.228	1472	58	**This work,** Brocheray et al., 2014
PROSECAN IV, KS10b	43.833	-2.050	550	50	**This work,** Mojtahid et al., 2013
SEDICAR/PICABIA, MD03-2693	43.654	-1.663	431	15	**This work,** Gaudin et al., 2006, Mary et al., 2015

Table 1: Location and references of the southern Bay of Biscay cores used in this study.

Depth in core PP10-07 (cm)	Sample	Material	Ref Number	mg C	$d^{13}C$	pMC corrected			**RAW 14C Age yr BP**			*corrected reservoir age / -400 yr BP*	**Calibrated age (median age) CLAM yr BP**	***-2σ yr***	***+2σ yr***	*Error yr*	*Confidence %*
4,5	PP10-07, 3-6 cm (TR1)	Bulk planktonic foraminifera	SacA39103	0,572	0,12	90,6	±	0,24	**790**	±	30	*390*	***423***	*353*	*493*	*70*	*92,6*
124,5	PP10-07 124-125 cm (TR2)	Bulk planktonic foraminifera	SacA39104	0,455	-1,1	82,1	±	0,24	**1590**	±	30	*1190*	***1149,5***	*1063*	*1236*	*86,5*	*95*
219,5	PP10-07 218-221	Bulk planktonic foraminifera	SacA 29590	0,7	0,2	77,5	±	0,19	**2050**	±	30	*1650*	***1618***	*1533*	*1702*	*85*	*95*
380	PP10-07 / 380	Bulk planktonic foraminifera	SacA 26975	0,78	-4,6	72,2	±	0,24	**2615**	±	30	*2215*	***2271***	*2175*	*2366*	*96*	*95*
720,5	PP10-07 / 720-721	Bulk planktonic foraminifera	SacA 26976	1	-0,9	58,8	±	0,22	**4265**	±	30	*3865*	***4380***	*4272*	*4487*	*108*	*95*
1050	PP10-07 / 1050	Bulk planktonic foraminifera	SacA 26977	1,1	-5,2	49,4	±	0,17	**5660**	±	30	*5260*	***6070***	*5970*	*6170*	*100*	*95*
1180	PP10-07 1180	Bulk planktonic foraminifera	SacA 29591	0,69	-0,3	44,6	±	0,14	**6490**	±	30	*6090*	***7007***	*6897*	*7116*	*110*	*95*
1540	PP10-07 / 1537-1543	Bulk planktonic foraminifera	SacA 26978	1,17	-1,9	33,8	±	0,17	**8705**	±	40	*8305*	***9371***	*9276*	*9466*	*95*	*95*
1731,5	PP10-07 1730-1733	Bulk planktonic foraminifera	SacA 29592	0,84	-0,8	33	±	0,12	**8900**	±	30	*8500*	***9556***	*9477*	*9635*	*79*	*95*
1981,5	PP10-07 1980-1983	Bulk planktonic foraminifera	SacA 29593	1	-1,5	31,6	±	0,12	**9270**	±	30	*8870*	***10093***	*9992*	*10193*	*101*	*92*

Table 2: Summary of AMS ^{14}C ages of core PP10-07 with calendar correspondences.

Figure caption

Figure 1: **A**: map showing the regional scheme of the main surface currents in the Bay of Biscay, drawn after the compilation of modern hydrological survey from Pingree and Garcia-Soto (2014). North Atlantic Current (NAC), Iberian poleward Current (IPC), and European Slope Current (ESC) are respectively represented by the red and orange arrows. The studied sedimentary cores PP10-07 and KS10b from the inner Bay of Biscay are shown in red. Additional Holocene records cited in the text are displayed by green squares. **B**: North Atlantic general circulation pattern (SPG: Subpolar Gyre, STG: Subtropical Gyre, EPC: European Poleward Current, after Lherminier and Thierry, 2015) with the location of the northern and southern sedimentary records discussed in the text. Core references: **1**-Brocheray et al., 2014; **2**-Mojtahid et al., 2013; **3**-Gaudin et al., 2006; Mary et al., 2015; **4**-Naughton et al., 2007a; **5**-Pena et al., 2010; **6**-Werner et al., 2013; **7**-Sarnthein et al., 2003; **8**-Giraudeau et al., 2004; **9**-Andrews and Giraudeau, 2003; **10**-Thornalley et al., 2009; **11**- Naughton et al., 2007b; **12**-Abrantes et al., 2011; **13**-Chabaud et al., 2014; **14**- Rodrigues et al., 2009; **15**-Martrat et al., 2007; **16**- Risebrobakken et al., 2011; **17**- Cisneros et al., 2016. **C**: SST evolution over the last centuries in the Bay of Biscay (from the MD03-2693 sedimentological record and from the compilation of Garcia-Soto et al., 2002) and comparison, from the top to the bottom with: the Global SST anomaly (after Kennedy, 2014), the Atlantic Tropical Cyclone Counts (after Landsea et al. 2010) and the NAO index of Hurell (http://research.jisao.washington.edu/data_sets/nao/).

Figure 2: Revised age models for cores KS10b, MD03-2693, and PP10-07 (left panels) compared to previous published age models (right panels with original references).

Figure 3: Mean Annual sea surface temperature (SST) records from the Western European margin. **A**: Holocene SST signals from cores PP10-07 and KS10b (this study) reconstructed using the Modern Analogue Technique (MAT) based on planktonic foraminifera (see Methods), and compared to SST signal of the adjacent core MD03-2693 (Mary et al., 2015). Black dots identify ^{14}C age control points. **B**: SST signals spanning the last 1500 years in the Bay of Biscay (core MD03-2693) based on MAT and from the Iberian Margin (core PO287-06, Abrantes et al., 2011) using alkenones. Reconstructed signals are compared with the AMO reconstruction of Mann et al., (2009). The dotted curve represents core MD03-2693 signal transposed on top of the two other curves. **C**: Holocene SST signals from the Iberian Margin using MAT based on planktonic foraminifera for cores MD99-2331 (after Naughton et al., 2007b) and MD95-2042 (after Chabaud et al., 2014) and Alkenones for cores D13882 (after Rodrigues et al., 2009) and MD01-2444 (after Martrat et al., 2007).

Figure 4: Comparison of annual SST Holocene signals from the Bay of Biscay (**A** and **B**) with records from the northern North Atlantic highlighting variations of the NAC intensity and SPG dynamics; **C**: SST signal of core MSM5/5-712-2 (Fram strait, Werner et al., 2013) and of **D**: core M23258 (Barents shelf, after Sarnthein et al., 2003), both reconstructed using the Modern Analogue Technique (MAT) based on planktonic foraminifera; **E**: Concentration of NAC indicator coccolith species in core MD99-2269 (North Iceland Shelf, after Giraudeau et al., 2004) and in **F**: core B997-330 (North Iceland Shelf, after Andrews and Giraudeau, 2003); The PP10-07 record is here also plotted by a thin dotted red line to underline the comparison; **G**: Holocene Storm Periods (after Sorrel et al., 2012) reconstructed from sedimentological evidence from a compilation of coastal cores in North-western Europe; **H**: core Rapid-12-1K (Thornalley et al., 2009) proxy for upper-water column stratification, calculated using derived Mg/Ca and $\delta^{18}O$ temperatures and salinities of *G. bulloides and G.*

inflata. Dotted vertical lines point out events of density difference between the near-surface and base of the seasonal thermocline in the southern Iceland basin. The topmost dark blue triangles and light blue vertical bands point to cold anomalies recorded in the southern Bay of Biscay (potentially corresponding to a weak SPG).. Pink bands conversely highlight periods of warmth which also correspond to enhanced NAC activity North of Iceland. Changes in gyre circulation dynamics are compared with the Holocene division of Wanner et al. (2008).

Figure 5: Gathering data and forcing: comparison of the Bay of Biscay (BB) signals (**A**: annual SST, **B**: XRF ratio in PP10-07, **C**: planktonic foraminifera absolute abundances in PP10-07, **D**: annual SST anomalies vs modern mean in PP10-07), with key Holocene records, i.e.: **E**: Bond et al. 2001 record; **F**: total solar irradiance reconstruction after Roth & Joos, 2013; **G**: annual SST anomalies in the Nordic seas (Eastern) digitized from Risebrobakken et al., 2011-Fig3. The dark blue triangles and light blue vertical bands point to cold anomalies recorded in the BB (potentially corresponding to a weak SPG).
On the left side are compiled data zooming over the last 4 ka with **A'**: BB annual SST; **B'**: reconstruction of the European temperature anomalies (from 30-year averages) of the PAGES 2k Network (2013); **C'**: Cantabrian speleothem $\delta^{13}C$ stack reflecting 4ka land surface temperature changes, digitized after Martín-Chivelet et al. 2011; **D'**: temperate pollen tree influx from the proximal Ria de Vigo, redrawn after Desprat et al., 2003, **E'**: Mg/Ca SSt anomaly in Minorca and related historical events after Cisneros et al. 2016 (Talaiotic Period -TP, Roman Period -RP, Dark Middle Ages -DMA, Medieval Climate Anomaly -MCA, Little Ice Age -LIA).

Figure 6: tentative scheme of North Atlantic oceanic circulation changes associated to contrasted BB SST scenarios (**A**: BB warm anomalies, **B**: BB cool events). This Figure,

primarily based on the Figure 1B, was constructed compiling previous works of Staine-Urias et al., 2013 and of Morley et al., 2014 (see also table E2). Squares identify the key records used in Figure 4 and 5 with colors pointed to warm/cool situation or empty when no clear trend is detectable.

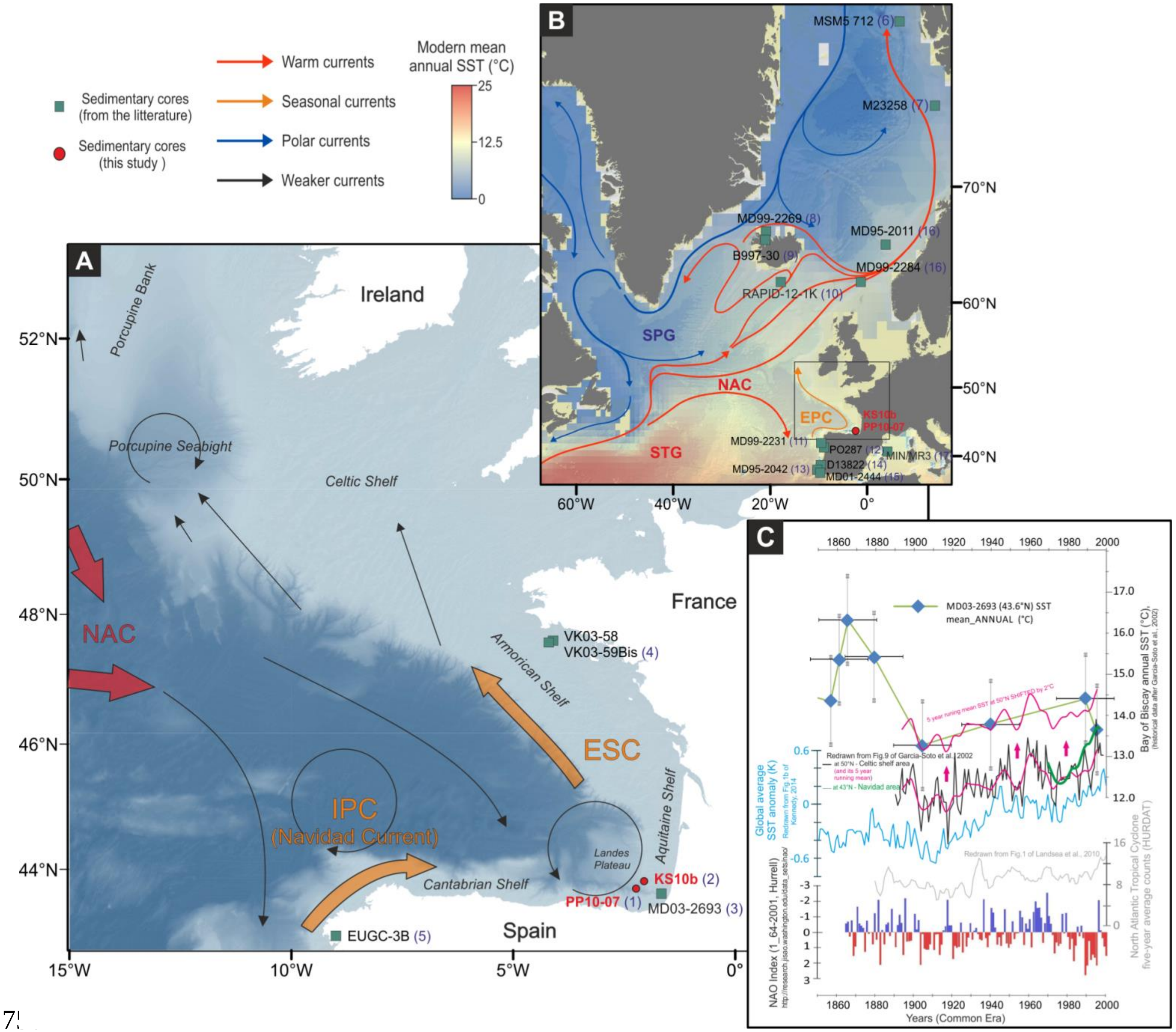


Figure 1 (revised)

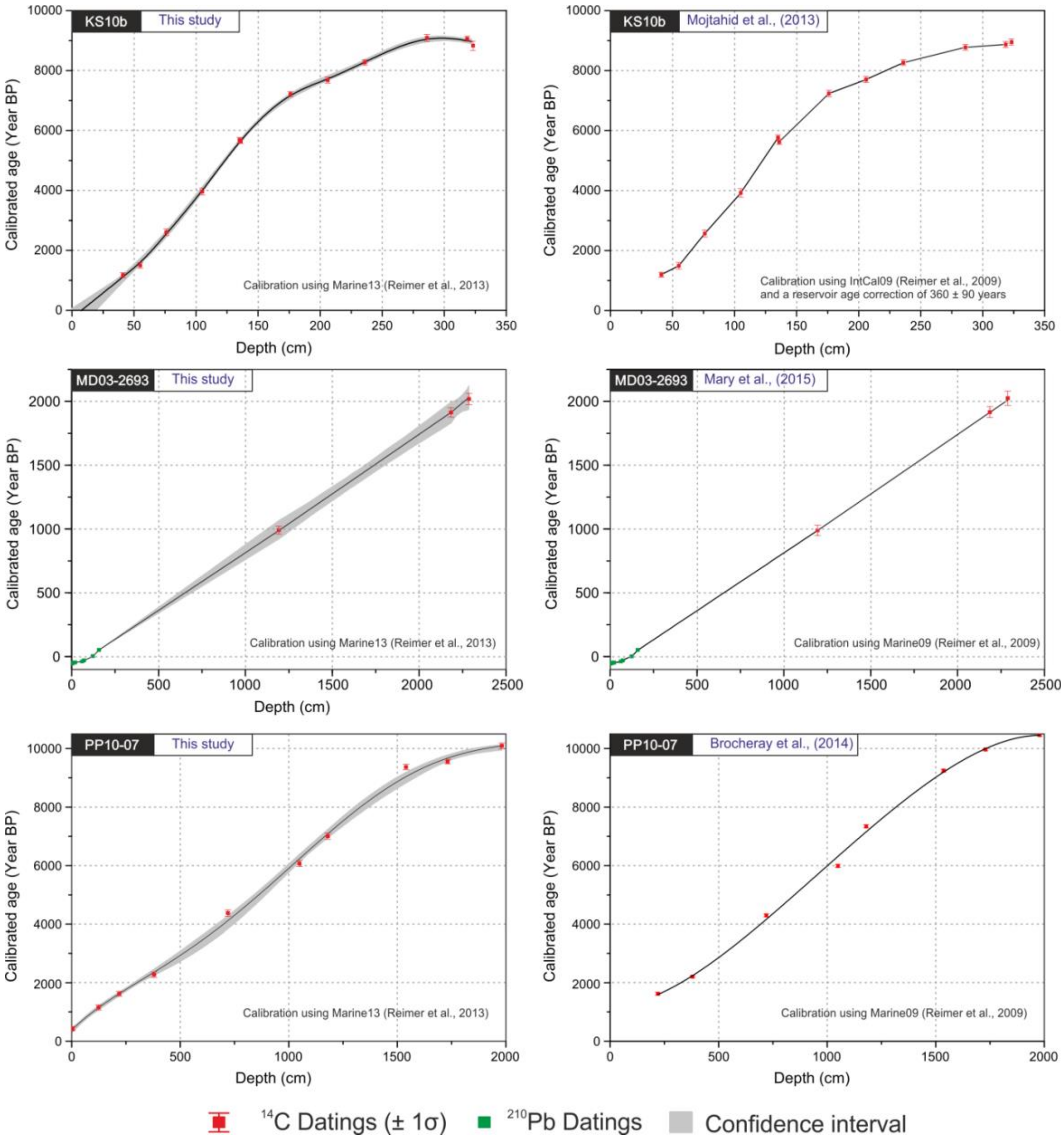

KS10b
This study
Calibrated age (Year BP)
Depth (cm)
Calibration using Marine13 (Reimer et al., 2013)
KS10b
Mojtahid et al., (2013)
Calibration using IntCal09 (Reimer et al., 2009)
and a reservoir age correction of 360 ± 90 years
MD03-2693
This study
Calibration using Marine13 (Reimer et al., 2013)
MD03-2693
Mary et al., (2015)
Calibration using Marine09 (Reimer et al., 2009)
PP10-07
This study
Calibration using Marine13 (Reimer et al., 2013)
PP10-07
Brocheray et al., (2014)
Calibration using Marine09 (Reimer et al., 2009)
14C Datings (± 1σ)
210Pb Datings
Confidence interval

Figure 2

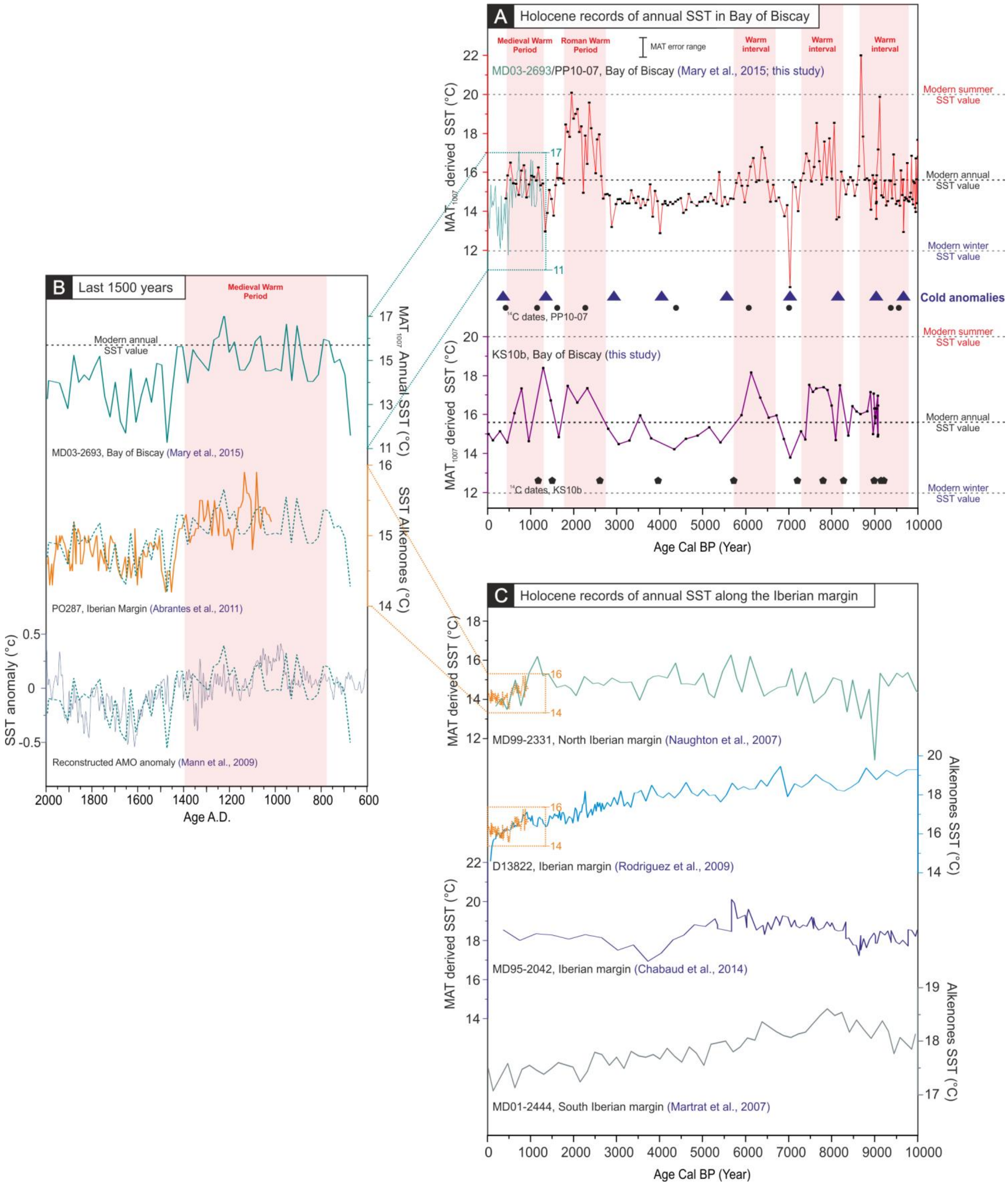
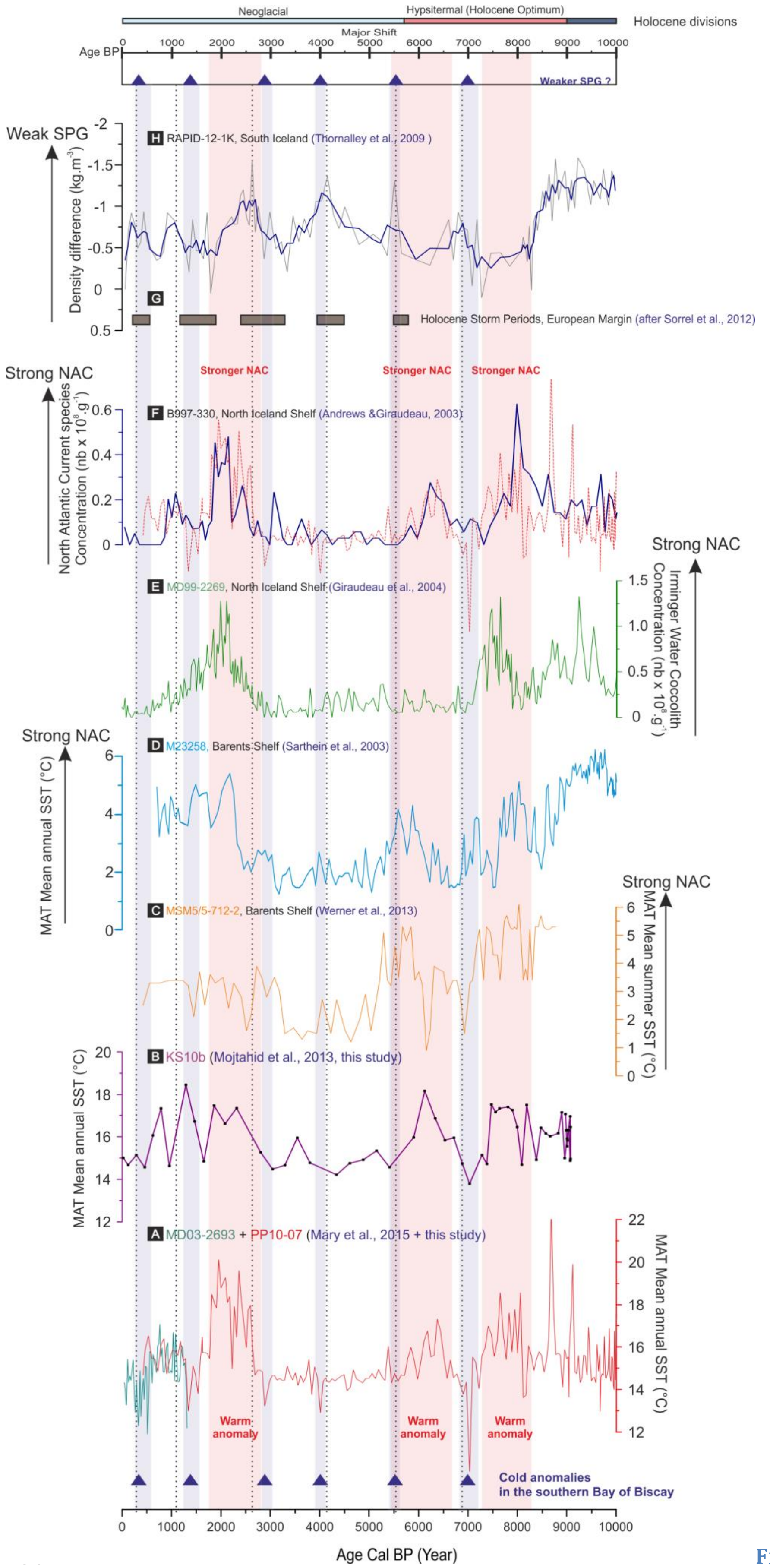
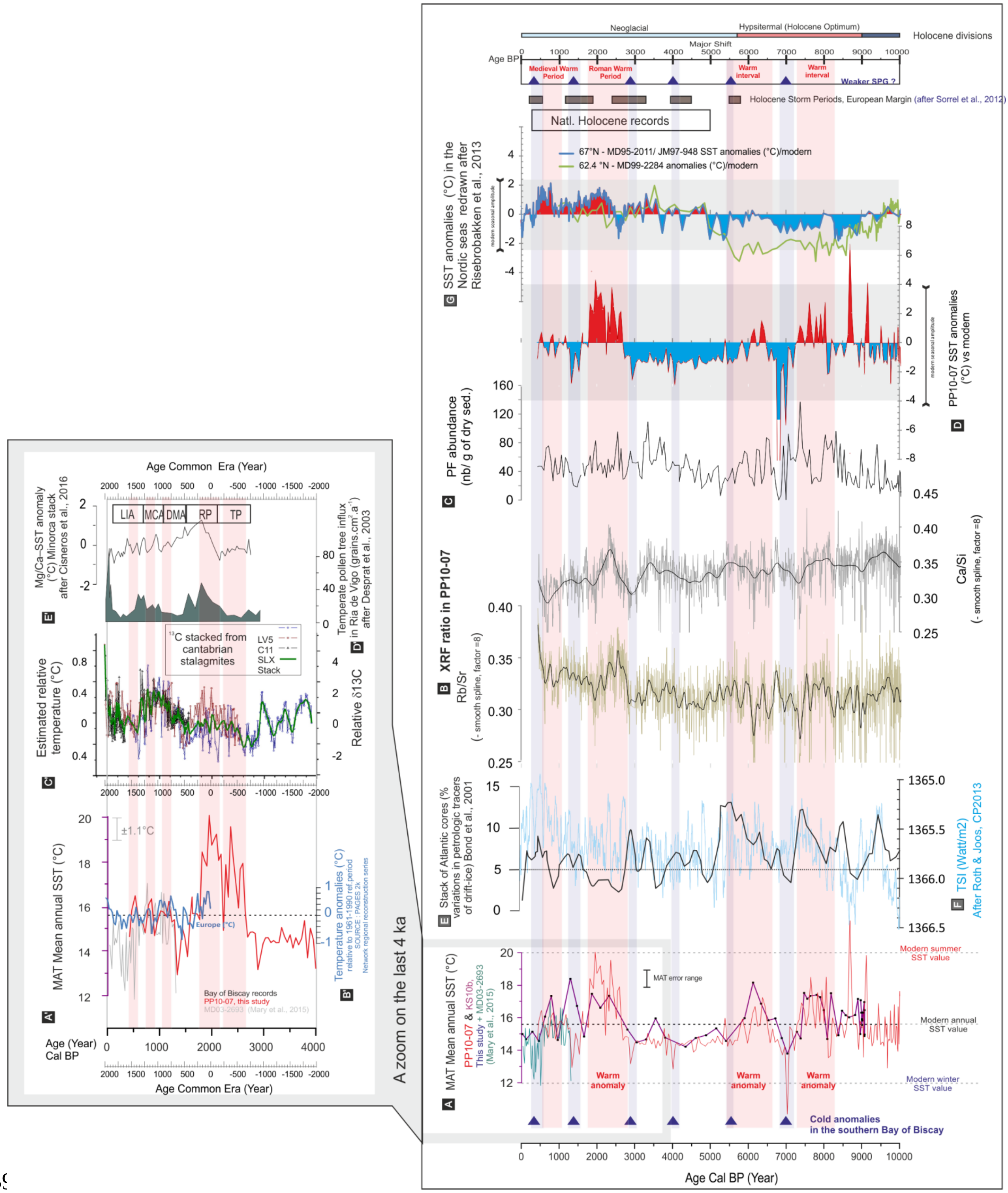

A Holocene records of annual SST in Bay of Biscay
Medieval Warm Period
Roman Warm Period
MAT error range
Warm interval
Warm interval
Warm interval
MD03-2693/PP10-07, Bay of Biscay (Mary et al., 2015; this study)
Modern summer SST value
Modern annual SST value
Modern winter SST value
Cold anomalies
14C dates, PP10-07
KS10b, Bay of Biscay (this study)
14C dates, KS10b
MAT1007 derived SST (°C)
Age Cal BP (Year)
B Last 1500 years
Medieval Warm Period
Modern annual SST value
MD03-2693, Bay of Biscay (Mary et al., 2015)
MAT1007 Annual SST (°C)
SST Alkenones (°C)
PO287, Iberian Margin (Abrantes et al., 2011)
SST anomaly (°c)
Reconstructed AMO anomaly (Mann et al., 2009)
Age A.D.
C Holocene records of annual SST along the Iberian margin
MAT derived SST (°C)
MD99-2331, North Iberian margin (Naughton et al., 2007)
D13822, Iberian margin (Rodriguez et al., 2009)
Alkenones SST (°C)
MD95-2042, Iberian margin (Chabaud et al., 2014)
MD01-2444, South Iberian margin (Martrat et al., 2007)
Age Cal BP (Year)

Figure 3



Neoglacial
Hypsitermal (Holocene Optimum)
Holocene divisions
Major Shift
Age BP
Weaker SPG ?
Weak SPG
Density difference (kg.m-3)
H RAPID-12-1K, South Iceland (Thornalley et al., 2009)
G Holocene Storm Periods, European Margin (after Sorrel et al., 2012)
Strong NAC
Stronger NAC
Stronger NAC
Stronger NAC
North Atlantic Current species Concentration (nb x 10^8.g^-1)
F B997-330, North Iceland Shelf (Andrews &Giraudeau, 2003)
Strong NAC
Irminger Water Coccolith Concentration (nb x 10^8.g^-1)
E MD99-2269, North Iceland Shelf (Giraudeau et al., 2004)
Strong NAC
MAT Mean annual SST (°C)
D M23258, Barents Shelf (Sarthein et al., 2003)
Strong NAC
MAT Mean summer SST (°C)
C MSM5/5-712-2, Barents Shelf (Werner et al., 2013)
MAT Mean annual SST (°C)
B KS10b (Mojtahid et al., 2013, this study)
A MD03-2693 + PP10-07 (Mary et al., 2015 + this study)
MAT Mean annual SST (°C)
Warm anomaly
Warm anomaly
Warm anomaly
Cold anomalies in the southern Bay of Biscay
Age Cal BP (Year)

Figure 4



Holocene divisions
Neoglacial
Hypsithermal (Holocene Optimum)
Major Shift
Age BP
Medieval Warm Period
Roman Warm Period
Warm interval
Warm interval
Weaker SPG ?
Holocene Storm Periods, European Margin (after Sorrel et al., 2012)
Natl. Holocene records
67°N - MD95-2011/ JM97-948 SST anomalies (°C)/modern
62.4 °N - MD99-2284 anomalies (°C)/modern
G SST anomalies (°C) in the Nordic seas redrawn after Risebrobakken et al., 2013
D PP10-07 SST anomalies (°C) vs modern
C PF abundance (nb/ g of dry sed.)
B XRF ratio in PP10-07
Rb/Sr
(- smooth spline, factor =8)
Ca/Si
(- smooth spline, factor =8)
E Stack of Atlantic cores (% variations in petrologic tracers of drift-ice) Bond et al., 2001
F TSI (Watt/m2) After Roth & Joos, CP2013
A MAT Mean annual SST (°C)
PP10-07 & KS10b, This study + MD03-2693 (Mary et al., 2015)
MAT error range
Modern summer SST value
Modern annual SST value
Modern winter SST value
Warm anomaly
Warm anomaly
Warm anomaly
Cold anomalies in the southern Bay of Biscay
Age Cal BP (Year)
A zoom on the last 4 ka
Age Common Era (Year)
LIA
MCA
DMA
RP
TP
E' Mg/Ca–SST anomaly (°C) Minorca stack after Cisneros et al., 2016
D' Temperate pollen tree influx in Ria de Vigo (grains.cm⁻².a⁻¹) after Desprat et al., 2003
C' Estimated relative temperature (°C)
13C stacked from cantabrian stalagmites
LV5
C11
SLX
Stack
Relative δ13C
A' MAT Mean annual SST (°C)
±1.1°C
Europe (°C)
B' Temperature anomalies (°C) relative to 1961-1990 ref.period
SOURCE : PAGES 2k
Network regional reconstruction series
Bay of Biscay records
PP10-07, this study
MD03-2693 (Mary et al., 2015)
Age (Year) Cal BP

Figure 5

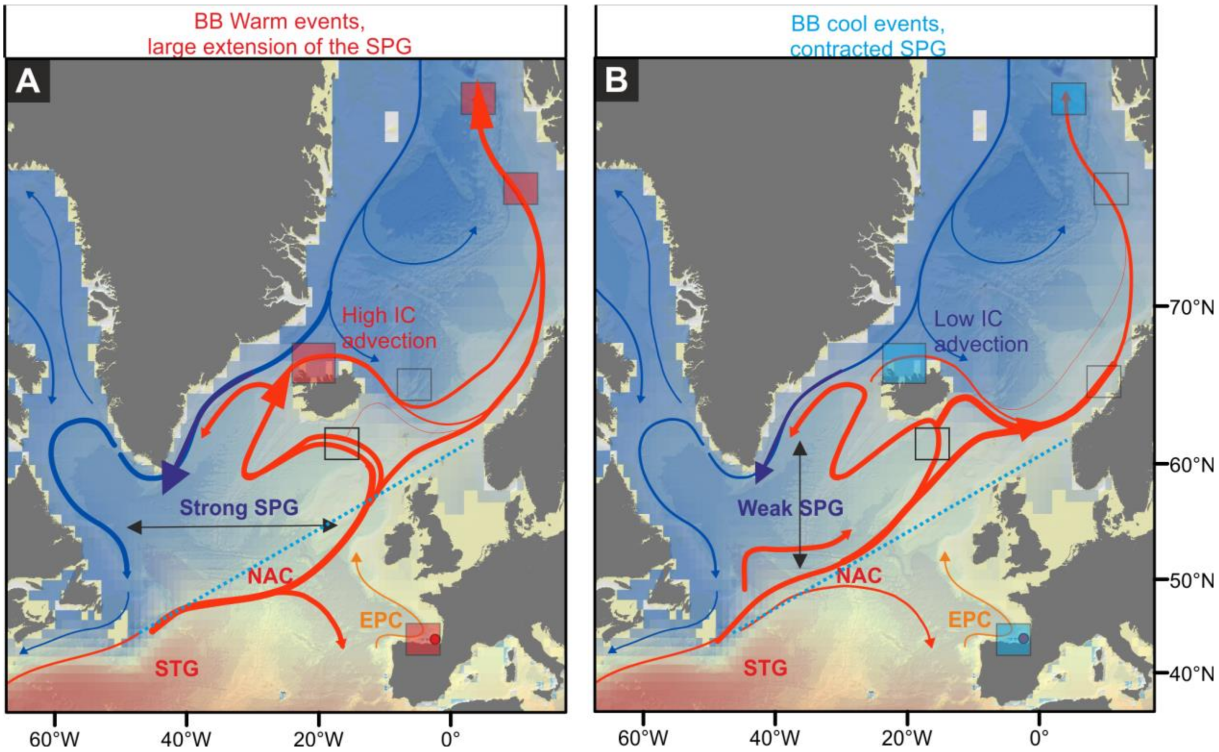

BB Warm events,
large extension of the SPG
A
High IC
advection
Strong SPG
NAC
EPC
STG
BB cool events,
contracted SPG
B
Low IC
advection
Weak SPG
NAC
EPC
STG
70°N
60°N
50°N
40°N
60°W
40°W
20°W
0°

Figure 6