The Climate of the Common Era off the Iberian Peninsula

Response to Anonymous Referee #1

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The authors thank referee 1 for his important contribution to improve the manuscript.

In general, the reviewer considers that the presented records provide useful information about climate variability offshore the Iberian Peninsula over the Common Era. However, the reviewer finds the paper too long and unable to pass a clear message, and suggests the paper to concentrate on answering a clear question.

The length of the paper has been substantially reduced. The introduction was shortened, the material and methods was reduced to the essential information and most of the detailed and considered important information is now compiled as Supplementary material. The essential information relative to the cores chronology was included in the methods and the individualized chronology section of the previous version was deleted. Detailed information on the age-model construction for the new sedimentary sequences is now also included in the supplementary material. The results and discussion section was subdivided and results are now presented separately. The discussion has also been re-organized around the specific questions raised by the data. Abstract and Conclusions have equally been re-written in what we hope to be a more concise style.

We certainly hope that the re-organization of the paper makes it easier to read and helps to better convey the message(s) included.

The reviewer considers also that the paper should definitely be proof read by a native English speaker, as many parts of the paper are very hard to understand lacking a sentence structure and words.

The new and much changed version has been thoroughly revised by a native English speaker.

Age model: The 3 new age models of the cores should be shown as an age-depth plot additionally to the table with the 14C dates. Moreover, a Bayesian age depth model should be performed to better constrain age uncertainties.

An explanation and data used for the definition of the age-models for the new three cores is now included in the supplementary material. However, in order to correctly respond to this comment, below we present a discussion on the methodology used for the age model construction of all 7 sedimentary sequences used in this paper, the comparison between methods and the basic data for the three new sedimentary sequences, including de age-depth models.

Chronology: The example of PO287-6

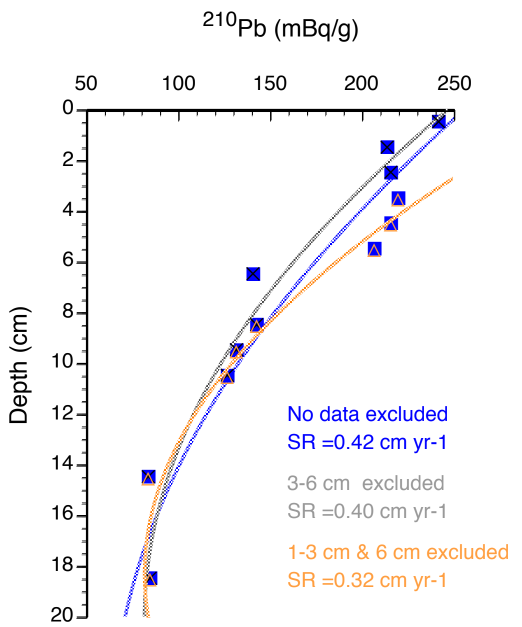
The age-model for the spliced sequence composed of cores PO287-6B and 6G (box, gravity) was constructed by combining two methods: (1) ^{210}Pb activity measured in box-core samples (Fig. 1A**)** which depending on the accepted model provides a sedimentation rate varying between 0.32 and 0.43 cm yr^{-1}; (2) four accelerator mass spectrometry (AMS) radiocarbon measurements (Leibniz-Laboratory for Radiometric Dating and Stable Isotope Research, Kiel, Germany) (Table 1). Two further ages were assigned through MS correlation to other well-dated cores recovered off Lisbon (Fig. 1B). Raw AMS ^{14}C dates were corrected for reservoir effect by 400 yr (Abrantes et al., 2005) and converted to calendar ages with the INTCAL04 data set (Reimer et al., 2004). The obtained calendar ages are presented in years Anno Domini (AD/CE).

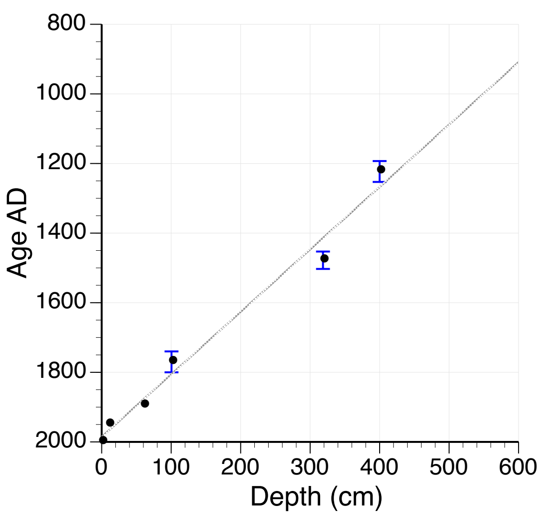
To develop a continuous record, the splicing of the long cores (piston and gravity) with the box-core (PO287-6B, 6G) was done through the Magnetic Susceptibility record (MS) of both cores (Fig. 1B). Further integration of the above-referred cores was based on the 1952 CE age found at 20.7 cm (depth corrected for compaction during sub-sampling) in box-core PO287-6B. Comparison of the PO287-6G MS record to sedimentary sequences from the Tagus system (Abrantes *et al.* 2005) was also done; Figure 1C depicts Depth *vs*. AD ages (with 2σ error) for PO287-6G with a linear best fit. An age that is within the error of the age estimated for the same depth using the sedimentation rate that results from a linear interpolation of the five considered levels (Table 1, Figs. 1B, 1C).

Given the uncertainty associated to the 14C dates, the establishment of an age model based on the interpolation between each dated level is normally avoided for sequences covering short time intervals (Jan Heinemeier, pers com.). An age/depth relationship defined by the linear best-fit line of the calibrated ^{14}C ages is the most common approach (e.g. (Narayan et al., 2010)). However we decided to compare age-depth models using both a linear and a polynomial best fit for core PO287-6G (Fig. 2). Both models give very close ages on the interval with dated levels, but the lack of dates at the base of core PO287-6G leads to older ages at the bottom of the record when using the polynomial solution.

Sample ID	Depth (cm)	C14 Age (RC = 400 yr)	Error	Age AD	Description
KIA 35149	100.5	160	25	1770	mixed benthics
KIA 29290	318.0	405	35	1478	mixed planktonics
KIA 35150	400.0	820	30	1223	mixed benthics

Table 1 – Results of ^{14}C AMS dating of the gravity core PO287-6G. Ages were reservoir corrected by 400 yr. Error column lists ± errors of 14C ages.





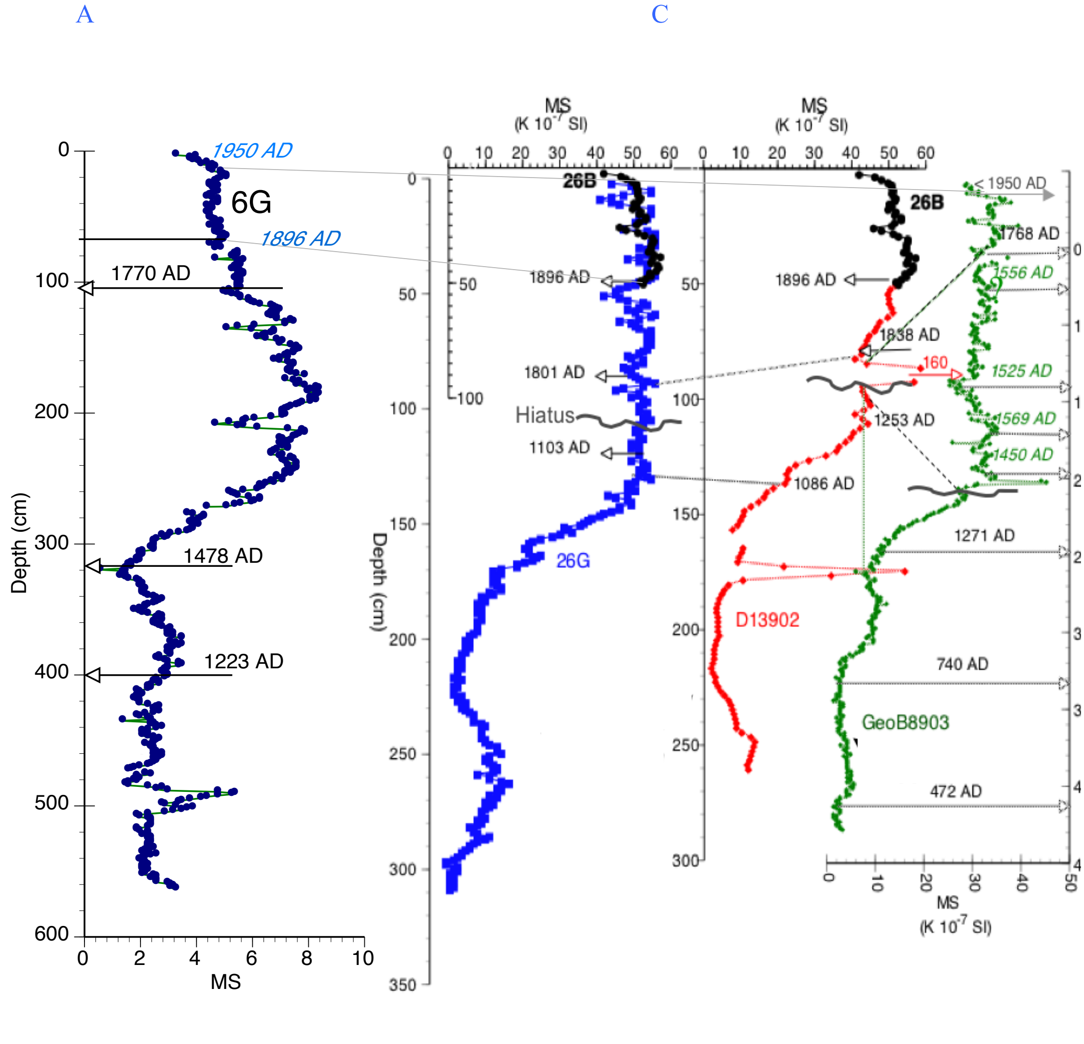


Figure 1 Information used to construct our age model; A) ^{210}Pb activity downcore PO287-6B; B) MS correlation of PO287-6G to sedimentary sequences from the Tagus system (Abrantes *et al.* 2005); C) Depth *vs.* AD ages (with 2σ error) for PO287-6G with a linear best fit.

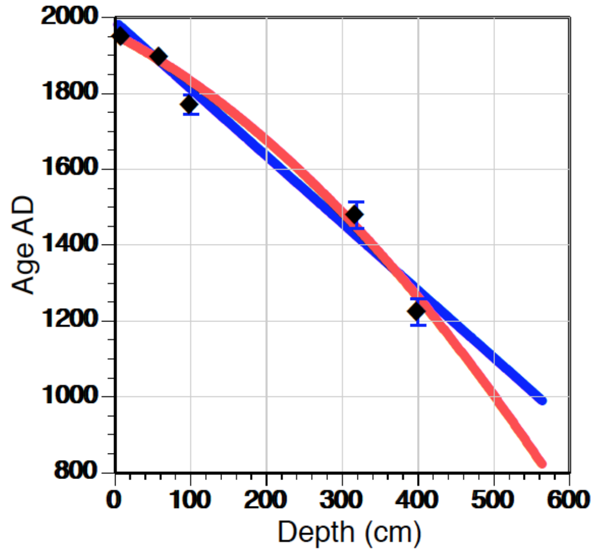


Figure 2 – Dated levels for core PO287-6G with a linear and a polynomial best fit for comparison.

Why the selection of a linear interpolation?

The assumption of a constant sedimentation rate was applied in Abrantes et al., 2005 (QSR) following the advise of Jan

Heinemeier (Aharus University ^{14}C dating center). According to this expert, in the case of records covering short time-scales, such as the last 2,000 yr, and with a relatively small number of age control points, it is better to use a linear best-fit curve.

Chronology of the Galiza, Minho and Algarve Cores

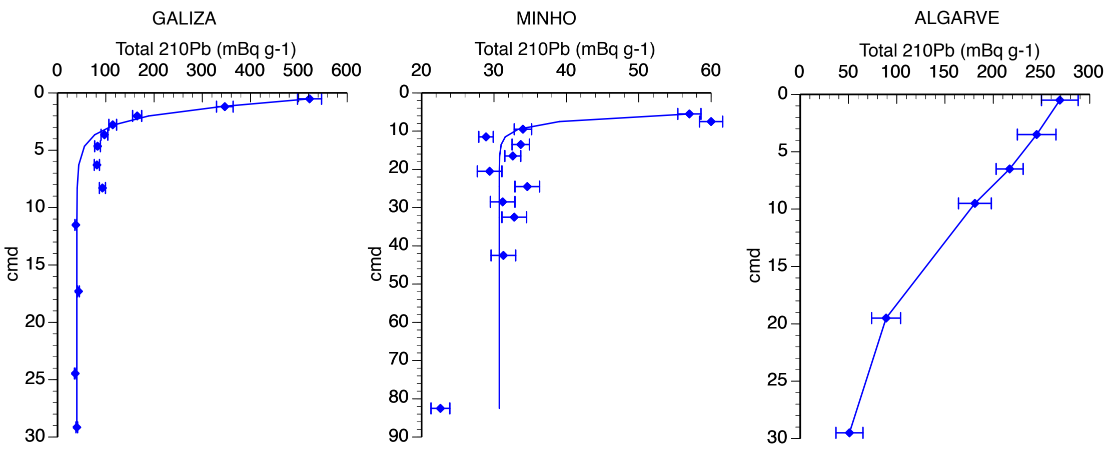


Figure 3 – ^{210}Pb activity downcore for the box-core GeoB11033-1 at the Galiza site and cores (Minho) DIVA09GC and (Algarve) POPEI VC2B.

The chronology of core GeoB11033-1 (Box-core of Galiza site) is based on a set of twelve ^{210}Pb data points, obtained in the upper 30 cm of the record, and one accelerator mass spectrometry ^{14}C date (AMS C14), obtained in planktonic foraminifera (Table 2, Fig. 3, Fig. 4).

Core ID and depth (cm)	Laboratory code	Sample Type	Conventional ^{14}C age (BP)	error	Calibrated age ranges at 95% confidence intervals	Age AD	Laboratory
GeoB11033-1							
27 - 28.5	OS-97151	Foraminifera	2430	25	746-530	-638	National Ocean Sciences AMS - WHOI
DIVA 09GC							
3 - 4	KIA 42919	Mollusk shell	465	25	1841-1859	1864	Leibniz Labor - Kiel
48-49	OS-97148	Foraminifera	1270	25	1057-1211	1133	National Ocean Sciences AMS - WHOI
57-58	KIA 42920	Mollusk shell	1730	30	602-728	660	Leibniz Labor - Kiel
68-69	OS-97149	Foraminifera	1990	25	298-482	400	National Ocean Sciences AMS - WHOI
83 - 84	KIA 42921	Mollusk shell	2380	30	-157 -33	-60	Leibniz Labor - Kiel
101 - 102	KIA 42922	Mollusk shell	2325	30	-87 - 95	11	Leibniz Labor - Kiel
POPEI VC2B							
130.9	Beta 278216	Mollusk shell	1220	40	1080:1274	1184	Beta Analytics
200.6	OS-97152	Foraminifera	2130	25	146:326	233	National Ocean Sciences AMS - WHOI
270.3	OS-97143	Foraminifera	3020	25	-902:-783	-837	National Ocean Sciences AMS - WHOI

Table 2 – Results of ^{14}C accelerator mass spectrometry dating (means ± SE) for cores GeoB11033-1 (Galiza), DIVA09CG (Minho) and POPEI VC2B (Algarve). Ages were corrected for reservoir effect by 400 yr and converted into calendar years (AD/CE).

^{210}Pb data was evaluated with the Constant Flux and Constant Sedimentation Rate model (CFCSR - (Appleby and Oldfield, 1992)) to date the upper 30 cm of the sediment core. The sedimentation rate was determined using the excess ^{210}Pb ($^{210}Pb_{excess}$) values, which is equivalent to the total ^{210}Pb activity minus the supported ^{210}Pb activity in equilibrium with sedimentary ^{226}Ra. The excess ^{210}Pb profile shows an exponential decrease with depth reaching the stable background value obtained using the ^{226}Ra activity at 27.5 cm depth. The data points at 6 and 8 cm depth were excluded (Fig. 3). The ^{210}Pb sedimentation rate estimated for the first 13 centimeters is 0.04 cm yr^{-1}. Top core age was assumed to be the core recovery year, 2006.

In the case of core DIVA09 GC (Minho site) the age-model construction is based in 12 ^{210}Pb data points distributed by 90 cm and 6 ^{14}C dates (AMS C14), obtained in marine material (shell and planktonic foraminifera) (Table 2, Fig. 3, Fig. 4). Background value was found at 9 cm depth. CFCSR model was defined excluding the ^{210}Pb values at 6 cm. Top age was assumed to be the core recovery year, 2009. The ^{210}Pb sedimentation rate estimated for the first 10 cm is 0.05 cm yr^{-1}.

The age-model of POPEI VC2B (Algarve site) is based on a set of eight ^{210}Pb data points, obtained in the upper 50 cm of the record, and eight accelerator mass spectrometry ^{14}C dates (AMS C14), obtained in marine material (shell and planktonic foraminifera) (Table 2, Fig. 3, Fig. 4).

^{210}Pb data was interpreted with the CFCSR model and the data for the upper 30 cm of the sediment, as the results of two additional data points (39-40 and 49-50 cm) were negligible. The stable background value found in all the other cores was not attained, but the ^{210}Pb estimated sedimentation rate is 0.52 cm yr^{-1}. Top age was assumed to be the core recovery year, 2008.

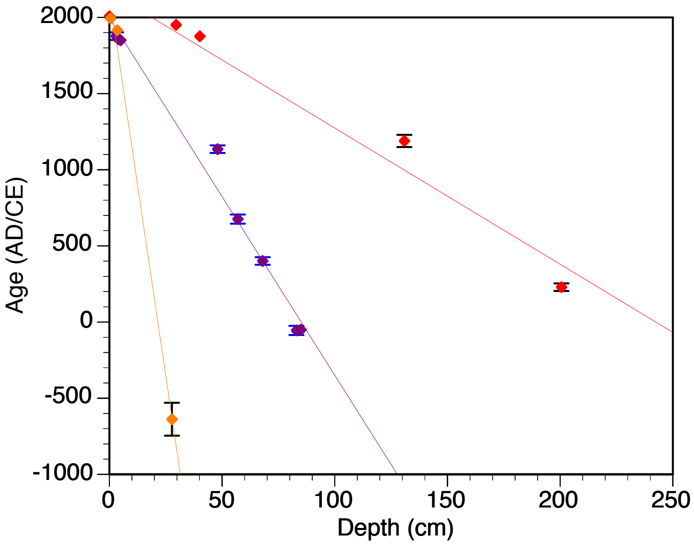


Figure 4. Depth *vs.* AD ages (with 2σ error) for cores GeoB11033-1 and GC at the Galiza site (orange), DIVA09GC (Minho, magenta) and POPEI VC2B (Algarve, red), with a linear best fit.

<u>Some specific comments below:</u>

Page 1 line 18: The Iberian Peninsula, at North Atlantic mid-latitude and the western extreme of the European continent, is a relevant area for climate reconstructions. – Rephrase sentence and what makes it a relevant area for climate reconstructions?

The sentence was changed following reviewer 1 suggestion.

Line 25: Is that even significant as the calibration error on alkenone SST is 1.5 C? Schouten et al., 2013, <u>http://dx.doi.org/10.1016/j.orggeochem.2012.09.006</u>

We used the calibration method defined by (Muller et al, 1998), which is a global calibration based on core-top sediments and mean annual climatological temperatures. The error associated with this calibration was defined in the original paper: "*the standard error is 1.5ºC, however considering that the Uk'37 values used for the global calibration were measured in about ten laboratories which partly used different methodologies, this differences could be minor rather attesting the robustness of the Uk'37 paleotemperature indicator*". Schouten et al. (2013) compiles previously published information in his Table 7.

Other calibration models use suspended matter (SOM) Uk'37 calibrated to in-situ measured SST (Conte et al., 2006; Gould et al., 2017) or are based on culture data (Prahl et al., 1988) and water column measurements (Prahl et al., 2005).

As a test we have used the three different models referred above to estimate SST in one of our sedimentary sequences (PO287- 6, Porto). Figure 5 shows no difference between the Muller and Prahl calibrations, while systematically lower SSTs are estimated when using Conte's calibration equation for core-top sediments (Mollenhauer et al., 2015). Independently of the used calibration method, the trends and amplitude of the observed variations are maintained all along the record even if variation is ≤ 1 ºC. As such, we conclude that our variability is significant, moreover for the definition of a long-term trend.

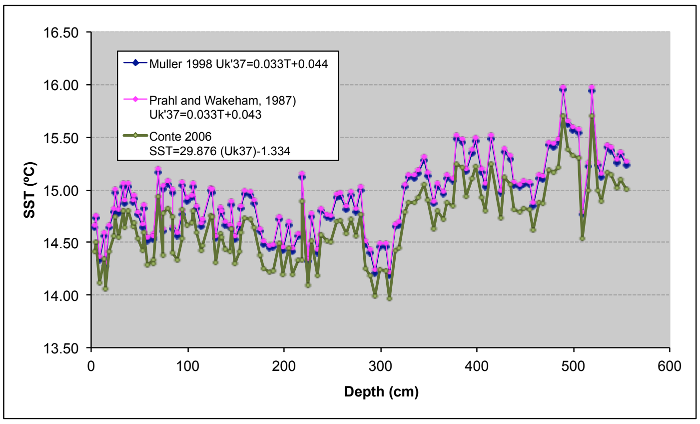


Figure 5 – Comparison of the SST variability estimated from three different calibration equations, along core PO287-6 (PORTO).

Besides, UK'37 derived SST data has been compared to those determined from GDGTs by Mollenhauer et al. (2015) for the Mauritania upwelling system and the authors conclusion is: *SST reconstructions based on alkenones are in excellent agreement with satellite data, and the entire seasonal amplitude of temperature variations at the sea surface is well recorded. In contrast, GDGT based temperature reconstructions using the logarithmic TEX86 calibration yields temperature maxima similar to observed maxima, but a reduced seasonal amplitude (warm bias).*

Page 2 Line 2: change to Medieval climate anomaly
Line 5: what does particular mean?

Wording has been changed

Line 7: "The intense precipitation/ flooding and warm winters but cooler intermediate seasons (spring and fall) observed for the early MWP imply the interplay of internal oceanic variability with the three atmospheric circulation modes, North Atlantic Oscillation (NAO), East Atlantic (EA) and Sandinavia (SCAND) in a positive phase".-how would the interplay of these 3 patterns cause the observed pattern?

We have profoundly changed the Introduction, and these patterns are now only referred. The effect of the three modes of atmospheric circulation on the climate of the Iberia Península (shown in figure 5 of Hernández et al. (2015)) is discussed in detail in the section Climate Forcing Mechanisms of the Discussion.

Line 15: rephrase-sentence like that makes no sense
Line 32: restructure
Line 33: delete Medieval Warm Period (MWP)
Page 3: Line 27: rephrase bad English
Page 4 Line 23-26: superficial statement needs more explanation
Line 30: change to: For that we combine the above mentioned published records with 3 new records located along the Iberian margin from 42_ N to 36 _N, covering the last 2,000 yr

The paper was revised taking into account all of referee 1 comments and requests.

Page 6: Line 4: Any additional proof that the cores are tracing river input despite pollen like BIT index

We did not use the BTI index, but as stated on lines 5 to 10 of the manuscript, "*Intensity of river discharge and on-land precipitation regimes were determined by using lipid compounds synthesized by higher plants, such as C23–C33 n-alkanes ([n-alc]) (e.g. Farrington et al. (1988); Pelejero et al. (1999); Prahl et al. (1994)) and the total pollen concentration (TPC)"*

Page 12 Line 17-18: not clear

Line 32: what does that mean important decrease?
Page 13 Line 15: what does the N stands for? Line 19: rephrase
Page 17 Line 20: Specific climate conditions – unclear what does specific indicate?

Requested revisions were taken into consideration

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The Climate of the Common Era off the Iberian Peninsula

Response to Anonymous Referee #2

Abrantes[1,2], Fátima; Teresa Rodrigues[1,2], Marta Rufino[2,3]; Emília Salgueiro[1,2]; Dulce Oliveira[1,2,4]; Sandra Gomes[1]; Paulo Oliveira[1]; Ana Costa[5]; Mário Mil-Homens[1]; Teresa Drago[1, 6]; Filipa Naughton[1,2,]

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This reviewer seconds the general opinion and concerns of reviewer 1 and prefers to present specific comments. We thank this valuable review and to not repeat ourselves, we invite the reviewer to please read our response to reviewer1. Specific comments are addressed below.

Specific comments:

-page 1: Abstract, first sentence, is not convincing at all. Please remove it.
-page 2: Lines 6-11, those lines are too complex and could not be properly understood without having a read over the modern climatology chapter.
-page 2: Line 23, perhaps cite Guiot and Cramer, 2016, Science, for a more recent assessment.

The new version of the paper takes into account all of Referee 2 requests and comments.

-page 3: Here the discussion would greatly benefit if the authors could add a series of very simple figures introducing the NAO, EA and SCAND modes of climate variability, in particular since the authors often refer to those modes later in the discussion.

In order to reduce the size and focus of the introductory text, the explanations and discussion of the impact of these modes of atmospheric circulation on the climate of the Iberia Peninsula is now only considered in the discussion section.

However, to clarify this important aspect, we have used the maps that show the regional effect of all three modes of atmospheric circulation (NAO, EA and SCAND) on the SST and precipitation for both winter and summer conditions over the Iberian Peninsula (Fig. 1), as proposed by Hernández et al., (2015) and presented in their figure 5 (Hernández et al., 2015). However, this work is published and we can only refer to the figure

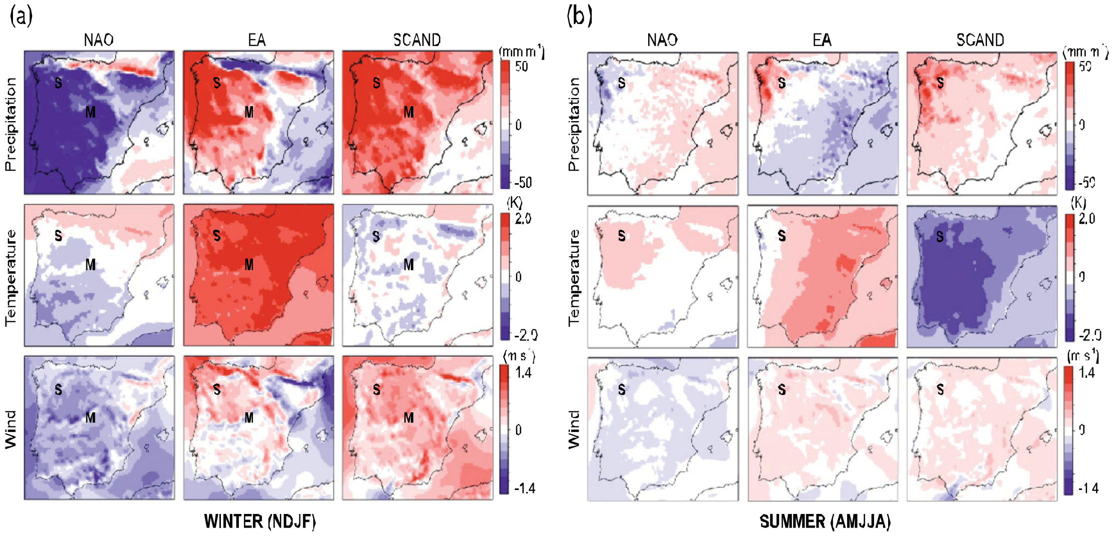

Figure 1 (Figure 5 of Hernandéz et al., (2015)). NAO, EA and SCAND modes effect on the mean precipitation, temperature and wind speed. 1 month lag time winter months (NDJF avg), and summer months (AMJJA avg).

-page 4: Here the reader is really lost, and could not remember any clear information at the end of the page.

The Introduction was fully rewritten and reduced in length.

-page 6: Line 31, please check that ''standardized" and ''scaled" are not referred to ''normalized" and ''standardized" instead.

We agree with the referee that there is some confusion over these terms, which are often interchanged. This is why for the purpose of clarity, we have added under brackets the mathematic operations that were actually carried out.

Normalizing typically means to transform the observations such that they look normally distributed <http://en.wikipedia.org/wiki/Normal_distribution>. Some examples of transformations for normalizing data are power transformations <http://en.wikipedia.org/wiki/Power_transform> (e.g. log).

Scaling simply means multiplying your observations by a constant c, which changes the scale (for example from nanometers to kilometers). Scaling is generally done for convenience, and does not imply any change in the distribution of the variable.

Standardizing generally means subtracting the mean and dividing by the standard deviation. But there often the terms are interchanged through the processes, i.e. scaled is named when we normalized, etc. the concepts are nested within each other. For example, the function 'scale' in R performs what is often named as standardizing the variables in a PCA, which corresponds to centering + scaling. Therefore, normalizing would be more transforming into a normal variable, which according to the bibliography it would not be applicable in this case. Either centering, scaling or standardizing would be ok for us if the referee considers so.

-page 8: Line 2, ''All age models : : : all accepted 14C dated levels" reads like you've discarded some of them. Please clarify the age model description.

The chronology for the three new cores will be included as Supplementary material. A presentation of the used data and methods is included in the response to Reviewer1. Given that these comments are available on line we decided by not repeating that information and respectfully ask Reviewer 2 to please read that response to Reviewer 1.

-page 9: Lines 23-31, the discussion on the most recent SST shifts could be either discussed later, or more developed (what is the great salinity minimum?). It is difficult to see what happens over the last 50 years.

We agree with reviewer 1 suggestion and a more detailed discussion on the SST variability within the Industrial Era section is now presented in the last point of the discussion of this new version of the paper.

-page 10: on the n-alcane concentrations, lines 1-10 please explain more how you calibrate the proxy. I would intuitively expect that dilution plays an important role, so that the more riverine runoff you get, the more alcanes would be diluted by terrigenous material, but it seems to be the contrary: : :
The more terrigenous material the higher the [n-alc], or is it diluted by the terrigenous component?

n-alkanes ([n-alk]) are long linear chain lipid molecules that mostly originate from cuticles of the vascular plants, and their concentration in oceanic sediments has been widely used as a proxy for river discharge (e.g. ((Elias et al., 1997; Grimalt et al., 1990)). Furthermore, previous work on Iberian Margin has shown a good agreement between [n-alk] and River flux (Abrantes et al., 2005; Rodrigues et al., 2009). The assessment of the value of this proxy at the regional scale, now included in the supplementary material, was done through the comparison of the [n-alk] data obtained for the most recent sediments of the Porto, Tejo and Algarve sites with the average river runoff for the Douro, Tejo and Guadiana Rivers during the NAO winter months (DJFM) for the years after 1991 and available at the Portuguese National Service for Hidric Resources (SNIRH) (http://snirh.inag.pt). The results reveal a significant (at $p>0.01$) Pearson correlation of 0.54 and $n=47$, confirming [n-alk] as a good proxy for evaluating the intensity of River runoff on the Iberian Peninsula.

Most of the sediments in these depocenters are muds (silt and clay) that result from the deposition of fine particles of terrigenous origin that are transported into the ocean in suspension by the river plumes (e.g (Abrantes et al., 2005; Abrantes et al., 2011)). Furthermore, most of the organic matter is bonded to the fine fraction of the sediment, in particular the clay fraction (Mil-Homens et al., 2007). The high correlation of the [n-alk] to other proxies of continental origin, such as Fe, has been demonstrated in previous papers for the Tejo area (Abrantes et al., 2005; Rodrigues et al., 2009). If we consider the sediments Fe content (cps) not only for the Tejo area but also for the Porto site and compare it to the n-alkanes measured concentrations in the same cores, a significant (at $p>0.01$) Pearson correlation of 0.47 and $n=250$ is found, revealing a parallel increase on both components of continental origin.

-chapter 5.3: please try to be more concise through sorting out the results and discussion separately. Why are you not discussing the LIA? Also, I find the wavelet analysis neither convincing nor useful to the discussion, and I don't see how you could extract significant periodicities longer than a century over time windows shorter than two centuries.

We do refer and discussed the LIA pattern found in our records, however, the fact that they can be explained by previously highly discussed and published climate processes lead us to concentrate on the discussion of the periods that reveal marked differences, the MWP and the last 500 years.

-figures: please check the captions. In general, there are too many panels.

We have looked into this aspect in detail, but still feel the need to maintain most of the panels. However, we have been very careful in referring to the figure's panel identification, every time one of them is mentioned in the text. We hope that this has made it easier to read previous figures, 5, 6 and 6 and will in the new version be figures 2, 3 and 4.

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The Climate of the Common Era off the Iberian Peninsula

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Abstract. The Mediterranean region is a climate hot spot, sensitive not only to global warming but also to water availability. In this work we document major temperature and precipitation changes in the Iberian Peninsula and margin during the last 2,000 yr, and propose an interplay of the North Atlantic internal variability with the three atmospheric circulation modes (ACM), (North Atlantic Oscillation (NAO), East Atlantic (EA) and Scandinavia (SCAND)) to explain the detected climate variability.

We present reconstructions of Sea Surface Temperature (SST derived from alkenones) and on-land precipitation (estimated from higher plant n-alkanes and pollen data) in sedimentary sequences recovered along the Iberian Margin between the South of Portugal (Algarve) and the Northwest of Spain (Galiza) (36 to 42 ºN).

A clear long-term cooling trend, from 0 CE to the beginning of the 20th century, emerges in all SST records and is considered to be a reflection of the decrease in the Northern Hemisphere summer insolation that began after the Holocene optimum. Multi-decadal/ centennial SST variability follows other records from Spain, Europe and the Northern Hemisphere. Warm SSTs throughout the first 1300 yr encompass the Roman Period (RP), the Dark Ages (DA) and the Medieval Climate Anomaly (MCA). A cooling initiated at 1300 CE, leads to 4 centuries of colder SSTs contemporary with the Little Ice Age (LIA) while a climate warming at 1800 CE marks the beginning of the Modern/Industrial Era.

Novel results include two distinct phases in the MCA, an early period (900 – 1100 yr) characterized by intense precipitation/ flooding and warm winters but a cooler spring-fall season attributed to the interplay of internal oceanic variability with a positive phase in the three modes of atmospheric circulation (NAO, EA and SCAND). The late MCA is marked by cooler and relatively drier winters and a warmer spring-fall season consistent with a shift to a negative mode of the SCAND.

The Industrial Era reveals a clear difference between the NW Iberia and the Algarve records. While off NW Iberia variability is low, the Algarve shows large amplitude decadal variability with an inverse relationship between SST and river input. Such conditions suggest a shift in the EA mode, from negative between 1900 and 1970 CE to positive after 1970, while NAO and SCAND remain in a positive phase. The particularly noticeable rise in SST at the Algarve site by the mid 20th century (± 1970), provides evidence for a regional response to the ongoing climate warming. The reported findings have implications for decadal-scale predictions of future climate change in the Iberian Peninsula.

1 Introduction

Today's anthropogenically-induced global warming poses a pressing problem on societies' sustainability (IPCC, 2013a, b). Regions such as the Arctic and the Mediterranean are highlighted as the most sensitive and potentially vulnerable to ongoing global warming (Climate, 2011; Giorgi, 2006).

Global and regional model simulations for the Iberian Peninsula forecast temperatures rising above the predicted global mean, and changes in precipitation consistent with long dry summers and a short and wetter rainy season particularly for the southern region (Guiot and Cramer, 2016; Miranda et al., 2002). Most of this knowledge is based on the analysis of instrumental data and modeling of global and hemispheric average conditions. However, given the limited time-span covered by the instrumental data, and to better comprehend the impact of climate warming it is essential to analyze and understand the response of the climate system in perspective of a longer time-scale. In light of the current warming, previous warm periods and warming transitions such as those occurring over the last 2,000 yr are of particular interest. Proxy-based climate reconstructions and modeling of the climate for the last 1 or 2 millennia in the Northern Hemisphere, have identified the late Roman Period (RP 0-500 CE), the Dark Ages (DA; 500-900 CE) and the Medieval Climate Anomaly (MCA; 900-1300 CE), also known as Medieval Warm Period (MWP), and the Little Ice Age (LIA; 1350-1850 CE), and attribute these climate variability mainly to external forcing such as solar and volcanic activity (Fernandez-Donado et al., 2013; Hegerl et al., 2006; Jones et al., 2001; McKim, 1998; Schurer et al., 2014). After 1900 CE, the rise in global mean atmospheric temperature is mainly attributed to the unprecedented increase of greenhouse gases in the atmosphere (IPCC, 2013a).

Throughout the last two decades, many high resolution 2,000 yr climate records have been generated from Iberian lake sediments (e.g. (Hernández et al., 2015; Jambrina-Enríquez et al., 2016; Morellón et al., 2009; Moreno et al., 2008; Valero-Garcés et al., 2006); speleothems (e.g. (Martín-Chivelet et al., 2011)) and marine sediments (e.g. (Abrantes et al., 2005; Abrantes et al., 2011; Desprat et al., 2003; Diz et al., 2002; Lebreiro et al., 2006; Pena et al., 2010).. Those individual as well as the compiled evaluations of climate evolution over Iberia (e.g. (Moreno et al., 2011; Sánchez-López et al., 2016) reveal multi-decadal to centennial climate variability in accordance with the main patterns identified for the North Hemisphere (Ahmed et al., 2013; Büntgen et al., 2011; Cook et al., 2004; Esper et al., 2002; Luterbacher et al., 2016; Moberg et al., 2005).

Additionally, given the dominance of the North Atlantic Oscillation (NAO) (Hurrell, 1995) in the Northern Hemisphere, most of the above works attribute the variability to changes in the prevailing modes of the NAO (Abrantes et al., 2005, 2011; Lebreiro et al., 2006). In recent years it has been proposed that the East Atlantic (EA) and Scandinavia (SCAND) modes also play a significant role on North Atlantic climate evolution (Comas-Bru and McDermott, 2014; Hernández et al., 2015; Jerez and Trigo, 2013). Sánchez-Lopez et al., (2016), on the basis of a spatiotemporal integration of several climate reconstructions, attempted to identify the role of those atmospheric patterns over the Iberian Peninsula. Their results reveal E-W and N-S humidity gradients from 0 to 500 CE and between 500 and 900 CE respectively, while between 900 and 1850 CE temperature and humidity conditions are more homogenous throughout the Peninsula. These conclusions support atmospheric pathways as the main control of climate variability in Western Europe on multi-decadal time-scales. However, Yamamoto and Palter (2016) observed a clear relationship between the Atlantic Multidecadal Oscillation (AMO) and the atmospheric circulation over Europe, with northerly winds associated to a positive state of the AMO and zonal winds to a negative state of the AMO. To better understand the role of oceanic and atmospheric processes on past climate and their relevance to the Iberian Peninsula's future climate, it is pivotal to obtain more high-resolution climate archives of the latest centuries and millennia. Here, we explore the main oceanic and atmospheric processes that drive complex spatial climate patterns over the Iberia Peninsula across the last 2,000 yr by integrating new records from the Iberian margin, Galiza, Minho and Algarve, with published datasets (Porto and Tejo; Abrantes et al., 2005, 2011; Lebreiro et al., 2006).

2 Oceanographic Conditions

The western coast of the Iberian Peninsula (Fig. 1) is characterized by contrasting oceanographic conditions between a spring-summer (April to October) coastal upwelling regime and a surface equatorward current (Fiuza, 1982, 1983; Peliz et al., 2002; Relvas et al., 2007), and a winter alongshore poleward warm counter current (Fiuza and Frouin, 1986; Peliz et al., 2005).

The spring-summer upwelling, constitutes the northern part of the Eastern North Atlantic Upwelling / Canary System and is connected to the presence of the Azores high-pressure system and the development of northerly alongshore winds (Fiuza, 1983). Upwelled waters are transported southwards by a jet-like surface current (Fig. 1C), the Portuguese Coastal Current, which is the coastal component of the Portuguese Current that branches of the North Atlantic Current, (Fiuza, 1982, 1983; Fiúza and Macedo, 1982). On the southern coast (Algarve), upwelling favorable conditions are rare, but western upwelled waters flow around Cape S. Vicente and along the south coast, (Fiuza, 1982, 1983; Fiúza and Macedo, 1982; Sánchez and Relvas, 2003) and can spread to its easternmost sector (Cardeira et al., 2013). This eastward flow of cold western upwelled waters alternates with the propagation of westward flows related to warm water and increased vertical stratification showing a direct relationship between flow velocity and water temperature (Garel et al., 2016; Relvas and Barton, 2002).

In winter, the prevalence of westerly/southwesterly winds leads to the intensification of the Iberian Poleward Current (Fig. 1B). This current, which is a branch of the Azores Current, consists of an upper slope/shelf break poleward flow that transports saltier and warmer (subtropical) waters (Peliz et al., 2005) depending mostly on the intensity of the southerly winds (Teles-Machado et al., 2015). Another important feature of the winter circulation over the western margin is the formation of coastal buoyant plumes, characterized by low salinities and temperature lower than the ambient shelf waters (Peliz et al., 2005). Such plumes result from the freshwater discharge from rivers, thus reflecting continental precipitation. Precipitation occurs mainly in winter, as a result of the moisture carried by the westerly winds into the Peninsula, and has important latitudinal differences, from 500 mm/year in the southeast to >3000 mm/year in the northwestern area (Miranda et al., 2002). As a consequence, buoyant plumes are mainly associated to the major northern Portuguese rivers (Minho, Douro, Mondego) but are also linked to the Tagus River, and can either develop into inshore currents (under typical winter downwelling conditions), or spread offshore under northerly wind conditions (Iglesias et al., 2014; Marta-Almeida et al., 2002; Mendes et al., 2016; Oliveira et al., 2007; Otero et al., 2008).

3 Material and Methods

This study combines proxy data previously published for sedimentary sequences collected off the Tagus River (PO287-26B, 26G, D13902 and D13882 designated as Tejo; Abrantes et al., 2005; Rodrigues et al., 2009) and Douro River (PO287-6B, 6G, designated as Porto; Abrantes et al., 2011) with new data from 3 other sites on the Iberian Margin (Table 1, Fig. 1). Two of the new sites are located in the northern area, off Vigo (GeoB11033-1 referred to as Galiza), and off the Minho River mouth (Diva09 GC, referred as Minho in this paper), and one core from southern Iberian/Algarve margin (POPEI VC2B, referred as Algarve). With the exception of the Galiza deep-sea core, all other sedimentary sequences were collected in the inner shelf in areas directly affected by river discharge.

Age-models of the three new cores (Galiza, Minho and Algarve), were constructed using the methods of Abrantes et al., (2005, 2011) and are based on accelerator mass spectrometry radiocarbon (AMS ^{14}C) and ^{210}Pb-inferred dates (section 1, Table SM1, Figs. SM1 and SM2 in Supplementary Material). Raw AMS ^{14}C dates were corrected for marine reservoir ages of 400 yr ±36 (Abrantes et al., 2005) and converted to calendar ages using INTCAL04 (Reimer et al., 2004). The obtained calendar ages are presented in years Anno Domini, now designated by Common Era (CE - McKim (1998).

Sea Surface Temperature (SST) was determined based on the ratio of alkenones ($U^{k'}_{37}$) synthesized by coccolithophores (phytoplankton group) (e.g. (Eglinton et al., 1992; Rosell-Melé et al., 1994; Villanueva and Grimalt, 1997). Lipid compounds synthesized by higher plants, such as C23–C33 n-alkanes ([n-alk]) (e.g. (Eglinton and Hamilton, 1967)) and the total pollen concentration (TPC) were used as indicators for river discharge intensity and on-land precipitation regime (e.g. (Rodrigues et al., 2009). Major changes in vegetation cover, that is, continental temperature and moisture conditions, were evaluated from pollen assemblages (Naughton et al., 2007).

Alkenones and higher plant n-alkanes were analyzed on 2 g of homogenized sediment using a Varian gas chromatograph Model 3800 equipped with a septum programmable injector and a flame ionization detector at the DivGM-IPMA laboratory according to the methods described in Villanueva (1996) and Villanueva et al. (1997). Analytical error was 0.5^{o}C. The concentration of each compound was determined using hexatriacontane as internal standard. For the calculation of Sea Surface Temperature (SST) we selected the globally defined calibration of Muller et al. (1998) ($U^{k'}_{37}$ = 0.033xSST-0.044). Both alkenone based SST and [n-alk] are widely accepted proxies for SST and river input, but to better understand our regional records, the significance of our high-resolution sediment data was assessed by comparison to NOAA daily Optimum Interpolation Sea Surface Temperature (OISST, V2 AVHRR-only) dataset (Fig. SM3 in Supplementary Material), and the river discharge dataset at *Sistema Nacional de Informação de Recursos Hídricos* (SNIRH).

Sample preparation procedures for pollen analyses followed the methods described in Naughton et al. (2007). Pollen and spores were counted using a Nikon light microscope at x550 and x1250 (oil immersion) magnification. Pollen identification was done via comparison with the pollen atlases of Moore et al. (1991) and Reille (1992). A minimum of 100 *Lycopodium* grains, 20 pollen types and 100 pollen grains, excluding the over represented *Pinus,* have been counted (Naughton et al., 2007). Pollen was gathered in two main groups: AP (arboreal pollen) including all trees and shrubs but excluding the over represented pine taxa, and the semi-desert plants, which groups xerophytic shrubs of semi-desert habitats (*Artemisia*, Chenopodiaceae, *Ephedra*).

To reduce the local variability signal and better evaluate the multi-decadal record at the regional level, a stack off all the cores was generated from the SST and n-alkanes original records on their original age-models. Each record was standardized (subtracting each value by the mean) and scaled (dividing the centered columns by its standard deviation). This technique weights high-resolution records more heavily and prevents interpolation across gaps or hiatuses from affecting the stack (Lisiecki and Raymo, 2005). Additionally, a test to the sensitivity of the stack to the bin-size and the inadequacies of the proxy data (Supplementary Material) reveals that the stack is insensitive to bin sizes (20 – 50 yr) and independent of data deficiencies (Fig. SM4). To focus on lower variability periods a similar stack was built using a 5-yr bin size and the Porto, Tejo and Algarve cores with sedimentation rate > 4 mm yr^{-1} (Fig. SM4, 3rd panel).

To investigate the existence of periodic signals and potential changes in their amplitude through time, we carried out a continuous time series transformation with a Morlet wavelet analysis on each dataset and stack (Torrence and Compo, 1998), after interpolation of the series to regular time steps. Interpolation was done using a cubic splines method and the temporal resolution of the interpolation was established as half of the absolute median difference between every consecutive time interval. Data was then detrended using a modified negative exponential curve, as required for the analysis. All statistical analysis was done using the libraries biwavelet (Akima and Gebhardt, 2016; Gouhier et al., 2016), from r-project (R Core Team, 2016).

Primary data for the new sedimentary sequences is archived in PANGEA (doi:10.1594/PANGAEA.882269).

4 Results

All the sedimentary sequences selected for this study have exceptionally high sedimentation rates in the upper levels, allowing for very high temporal resolution of 2-3 yr in the top sediments. In the older part of the sequences, larger sampling intervals and/or lower sedimentation rates provide a temporal resolution of ±30 yr. Additionally, the analyses of SST and multiple proxies for on-land precipitation from the same sediments, allows us to accurately evaluate the coupled ocean and land variability without chronological ambiguity. Furthermore, to better assess the regional value of Uk'$_{37}$-SST and [n-alk],

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Formatted: Font:(Default) Times New Roman, 10 pt sediment derived variables were compared to climatological datasets (sections 2 and 3 in Supplementary Material). Results validate the proxies and reveal that in the west coast SST compares to winter climatological data but in the Algarve SST mimics spring-fall (Fig. SM2), providing the opportunity to disentangle winter from spring-fall conditions in the region.

4.1 Sea Surface Temperature (SST)

SSTs are minima off Porto (14 to 16 ºC), maxima in the Algarve (17 to 20 ºC), while average temperatures are observed in the Tejo, Minho and Galiza (15 to 18 ºC) as shown in Fig. 2A by the alkenone-derived SST reconstructions for all 7 Iberian margin records. The temperature difference between the areas is maintained throughout the last 2,000 yr but the amplitude of decadal-secular variability is higher at the Tejo and Algarve sites (3ºC) than the 1.5 ºC detected in the northern sites (Porto, Minho and Galiza) (Fig. 2A). Moreover, the SST stack (Fig. 2B), reveals an overall long-term cooling trend from 0 CE to the beginning of the 20th century, with a stronger gradient at the Tejo (2.5 ºC/ 2,000 yr) than at the other sites (1ºC/ 2,000 yr) (Fig. 2A). This long-term cooling follows the gradual decrease of northern Hemisphere summer insolation across the Holocene reported for this region by Rodrigues et al. (2009), but also observed in other European and worldwide records (Ahmed et al., 2013; Luterbacher et al., 2016; McGregor et al., 2015).

Superimposed on the long-term cooling, both the individual SST records (Fig. 2A) and the SST stack (Fig. 2B) display century-scale variability comparable with that recorded in both the oceanic and continental environments of northern Spain (Fig. 2C, D) as well as in other European and Northern Hemisphere records (Fig. 2E, F) (Diz et al., 2002; Luterbacher et al., 2016; Martín-Chivelet et al., 2011; Moberg et al., 2005). Relatively high SSTs occur during the first 9 centuries encompassing the late Roman period (RP; 0 – 500 CE) and Dark Ages (DA; 500 -900) (Fig. 2A, B), mainly at the Southern sites (Tejo and Algarve; Table 2). Consistently warmth conditions are also recognized at all sites between 900 and 1300 CE within the MCA (Fig. 2A, B). The Western Iberia records reveal a warmer first phase in the MCA (900 – 1150 CE) in agreement with data for thee NE North Atlantic (Cunningham et al., 2013). However, at the Algarve site SST decreases during the MCA, between 800 and 1100 CE followed by an increase of ± 1 ºC between 1100 and 1300 CE.

A transition from warm to cold climatic conditions starts around 1300 CE (Fig. 2B) associated with the Wolf solar minimum (Fig. 2H) (Bard et al., 2007). Cold conditions prevail for most of the 15th to 18th centuries in Western Iberia, during the well-known LIA (Bradley and Jones, 1993). SSTs are colder than during MCA by an average 0.5 ºC in the northern sites and 1.2ºC in the southern sites, particularly in the high resolution LIA record from the Algarve (Fig. 2A). Abrupt cold episodes are synchronous with solar minima and major volcanic events (Fig. 2G, H; e.g. (Crowley and Unterman, 2013; Solanki et al., 2004; Steinhilber et al., 2012; Turner et al., 2016; Usoskin et al., 2011)).

At 1800 CE an increase in SST marks the transition to warm modern times referred to as the Industrial Era. During the 20th century, unusually large decadal-scale SST oscillations are recorded in the southern sites, in particular in the Algarve, where a more abrupt rise in SST occurs by the mid 20th century at around 1970 CE (Fig. 2A) coinciding with the Great Solar Maximum (1940 – 2000; (Usoskin et al., 2011).

Such increase in the amplitude of SST variation during the last 50 years, in particular at the Algarve site, although attributable to better proxy preservation in the more recent sediments (Calvert and Pedersen, 2007), is certainly also a reflection of the regional reaction to an intensification of climatic extremes, an expected response to the ongoing climate warming (IPCC, 2013a; Miranda et al., 2002).

4.2 Continental Precipitation

At present there is a clear north-south difference in the precipitation regime, with higher mean annual precipitation in the north versus the southern region (Miranda et al., 2002). In our records, the lowest lipid compounds synthesized by continental plants ([n-alk]) (100-700 ng/g) are found at Galiza, the deepest (1873 m) and more oceanic site, while the highest [n-alk] (1000 to 7000 ng/g) mainly reflect the large Douro River discharge. The Minho, Tejo and Algarve sites that are influenced by intermediate mean annual discharge rivers Minho, Tagus and Guadiana (Miranda et al., 2002), show intermediate [n-alk] (700 - 4000 ng/g) (Fig. 3A).

The total [n-alk] stack (Fig. 3B) highlights abrupt decadal-scale variability of river discharge throughout the first 900 yr, with relatively lower mean values during the DA (500 to 900 CE) (Fig.3B). In the MCA, a strong positive deviation occurs in the early MCA (980-1100 CE), mainly reflecting the extreme river discharge in Porto, since reduced river discharge is recorded at the Tejo and Algarve sites (Fig. 3A). From 1100 to 1200 CE river discharge is still low in the southern cores and Porto reaches minimum values. After 1200 CE, throughout the late MCA to the beginning of the LIA, a gradual increase in the total [n-alk] reflects a persistent river flow at all latitudes (Fig. 3A, B). As found for SST, river input during the Industrial Era shows large amplitude variability in the southern cores and the Algarve in particular.

Iberian precipitation variability reflects changes in river discharge intensity, which can also be estimated from oscillations in TPC (Naughton et al., 2009). TPC data, although at a very low temporal resolution, is available for 3 locations, Minho, Tejo and the Algarve (Fig. 3C). The TPC data suggests a much larger river discharge during the RP at the Tejo (core D13882) than in the Minho or the Algarve. During the DA and the MCA TPC-derived riverine input/precipitation is higher at the Minho and Tagus hydrological basins than in the Algarve, but at 1400 CE the Algarve record rises to higher values comparable to those observed at the Minho, in accordance with [n-alk] (Fig. 3A, C).

To substantiate our [n-alk] and TPC records of on-land precipitation, we compared our data to various reconstructions and historical documents of Iberian flood events. For the Tagus, flood reconstructions based on the hydrological basin terraces (Benito et al., 2005; 2004; 2003) and the Taravilla Lake sediment record from the headwaters of the Tagus River (Moreno et al., 2008). Historical documentation was provided by Tullot (1988) for the Douro and Minho Rivers, and by Barriendos and Rodrigo (2006) for most Iberian Peninsula basins including the coastal Mediterranean and daily journals for the most recent flood events of the Guadiana River (Barriendos and Martin-Vide, 1998; Barriendos and Rodrigo, 2006; Cabrita, 2007; Varzeano, 1976) (Table 3; Fig. 3). Despite age uncertainties, the stack [n-alk] maxima between 980 and 1100 CE coincides with reports of major flooding events in both the Douro and Minho Rivers (Tullot, 1988). Other periods marked by strong precipitation occur in the MCA between 1180 – 1200 CE, and again in the beginning of LIA, from 1450 to 1470 CE (Tullot, 1988). At the Tejo site the [n-alk] record also agrees with significant river flooding phases (1200 – 1300 CE; 1950 – 1980 CE) (Benito et al., 2004; Benito and Hudson, 2010; Benito et al., 2003). The Algarve site, located 80 km to the west of the Guadiana River mouth appears to be recording not only the most recent newspaper's reported flooding events of 1876 and 1979 CE (Cabrita, 2007; Varzeano, 1976), but also the Atlantic basin flooding events (Barriendos and Rodrigo, 2006; Benito et al., 2004). The similarity of the independently identified records of storm/flooding periods for the various regions, leads to the conclusion that the maxima in [n-alk] can indeed be attributed to extreme precipitation and flooding conditions (Fig. 3).

4.3 Atmospheric Temperature

Arboreal (AP) and semi-desert pollen variability at the Minho, Tejo and Algarve sites were compared with the same pollen curves from the Ria de Vigo (Desprat et al., 2003) and were found to reflect the main forest/climate changes over the last 2,000 yr (Fig. 4A, B). Major forest expansion, revealed by increasing AP percentages, occurs during the RP and the MCA, indicating relatively warm conditions on-land (Fig. 4B). In contrast, a reduction of the forest cover, revealed by the decrease of arboreal pollen, suggests relatively cold conditions during the LIA (Fig. 4B). Between 1700-1800 CE there is a strong decrease of arboreal pollen in Algarve and Minho suggesting an abrupt cooling episode over Iberia (Fig. 4B). After 1800 CE a new increase in AP reflects climate warming over the continent. AP variability in western Iberia over the last 2,000 yr shows no clear match with European summer atmospheric temperature or spring precipitation (Fig. 4F, G), but agrees with the general trend of Northern Spain's stalagmite T-anomaly (Fig. 4E) (Martín-Chivelet et al., 2011) and AP variability at the Ria de Vigo (Fig. 4B) (Desprat et al., 2003).

Semi-desert plant values are highest at the Algarve (although with a modest 8% contribution), lower at the Tejo site and further reduced at the Minho, showing clearly the north to south precipitation contrast (Fig. 4A). Between 1700 and 1800 CE (within the LIA), a marked decrease of both arboreal taxa and semi-desert plants is observed and co-occurs with abrupt shifts between periods of increased frequency of strong rain events (Barriendos and Martin-Vide, 1998) and periods of prolonged drought (Barriendos, 2002; Benito and Hudson, 2010). Furthermore, this interval also coincides with a period of stable temperature in Northern Spain, and minima in European seasonality and spring atmospheric temperature in Europe (Fig. 4E, H, I; (Luterbacher et al., 2004) as well as a minimum in spring-summer and winter precipitation (Fig. 4C, J, K; (Martín-Chivelet et al., 2011; Romero-Viana et al., 2011; Touchan et al., 2005)).

5. Discussion

5.1 Climate Forcing Mechanisms

Climate reconstructions for the Iberian Peninsula are complex because the seasonal variation of the oceanographic system along the Iberian Peninsula margin generates multiple conditions which combination is likely to vary through time. Nevertheless, the use of multiple proxies for each core, and at several sites, together with the regional anomaly stack, allow for the more robust climatic configurations to be identified. Furthermore, our assessment of the regional SST records (Supplementary Material, Fig. SM2) indicates that SSTs are comparable with winter temperatures in the west coast while in the Algarve SST match spring-fall temperatures (Fig. SM2), giving us the opportunity to disentangle winter from spring-fall conditions in the region.

The Iberian Peninsula margin was relatively warm from 0-1300 CE, in particular during the final stage of the RP (0- 500 CE) and the MCA (900-1300 CE), while SST slightly decreases during the DA (500 -900 CE) (Fig. 2B). A clearly colder LIA lasts from 1350 to 1850 CE, when a rise in SST marks the transition to modern times / Industrial Era. This initial augment in SST is followed by a second more abrupt mid 20th century SST rise, particularly evident in the southernmost site (Fig. 2A).

In terms of on-land precipitation, the early MCA is a period of extreme precipitation and flooding, mainly from the Douro River (Porto site) (Fig 3A, B). During the LIA, frequent but less extreme precipitation, is inferred at all sites with apparent periods of flooding that are in agreement with other flooding records (e.g. (Barriendos and Martin-Vide, 1998; Benito et al., 2005; Cabrita, 2007; Moreno et al., 2008; Tullot, 1988; Varzeano, 1976). Southern Iberian margin records also show evidence of the well-known major storm events of the 20th century.

The dominant large-scale climate mode operating in the Northern Hemisphere is the North Atlantic Oscillation (NAO) (Hurrell, 1995). Being mainly a winter season mode that varies on scales of days to decades, it translates into strong northerly winds and coastal upwelling favorable conditions during positive phases, while during NAO negative phases (also known as "blocked"), westerly/southwesterly winds predominate and result in very cold winters and increased storm activity (Hurrell, 1995; (Trigo et al., 2004).

Other prominent atmospheric circulation modes, the EA and the SCAND (Comas-Bru and McDermott, 2014; Jerez and Trigo, 2013), constitute second leading modes that interplay with the NAO. Their temporal variability must have also played a role on climatic evolution in the North Hemisphere. The EA has a strong influence on the strength and location of the NAO dipoles mainly on multi-decadal time-scale, and exerts major control on winter and summer temperature over the Iberian Peninsula (Hernández et al., 2015). The SCAND functions as a blocking high-pressure system that changes the westerly winds path and influences southwestern Europe mainly during its positive phase, when it contributes to below average temperatures and above average precipitation (Hernández et al., 2015). The regional effect of all three ACMs on SST and precipitation over the Iberian Peninsula, for winter and summer periods, is presented in figure 5 of Hernández et al. (2015). Bearing in mind the Atlantic coast, besides the negative relationship observed between NAO and winter precipitation, the EA and SCAND are also positively related to winter precipitation, particularly on the Northern Iberian Peninsula. In summer, there is a slight positive relationship between SCAND and precipitation in the north but an important negative effect with temperature in most of the south.

The compilation of Sánchez-Lopes et al, (2015), concludes that the climate of the Iberian Peninsula during the last 2,000 yr has been modulated by the combined effect of two main modes of atmospheric circulation, the NAO and the EA. Negative NAO and positive EA generate warm atmospheric temperatures and higher humidity in the west and south of the Iberian Peninsula during the RP. NAO positive and EA negative cause a more humid north with a W-E humidity gradient during the DA. Consistently warm and dry conditions during the MCA throughout the Iberian Peninsula are attributed to NAO positive and EA positive modes. On the contrary, NAO and EA negative modes are considered to explain the cold and wet winters, as well as, the cold summers proposed for the LIA.

Although our results might be explained by the above-described mechanisms proposed Sánchez-Lopez for the RP, the DA and the LIA (Figs. 2,3,4), the climate conditions detected in the MCA and the Industrial Era, need further discussion.

5.2 The particular case of the MCA and the industrial era

5.2.1 The MCA: precipitation distribution and the storm track

Dry and warm winters as well as warm summers are likely to be generated by the prevalence of NAO and EA positive modes as proposed by Sánchez-Lopes et al., (2015). Stronger coastal upwelling conditions have also been suggested to explain the productivity record of the Tejo site. This would imply prevailing northerly winds and an active Portuguese Current, which would equate to a positive NAO-like state or frequent occurrence of extreme NAO maxima during the MCA (Abrantes et al, 2005), that agrees with the NAO reconstruction of Ortega et al., (2015). Furthermore, forest expansion indicates relatively warm conditions in both the northwestern and southern Iberian Peninsula (Fig. 4B), and are in good agreement with atmospheric temperatures over NE Spain (Fig. 4C; (Martín-Chivelet et al., 2011) suggesting similar on-land conditions across northern Iberia.

However, our records show distinct conditions for the early MCA (900 - 1100 CE) where warm winters, cooler spring-falls and extreme precipitation characterize the Northern Iberian Peninsula (Fig. 5). Increased fluvial input during the MCA, particularly intense around 1000 CE is also observed at other sites in Northern Iberia; Ria de Vigo (Álvarez et al., 2005) and Ria de Muros (Lebreiro et al., 2006). On the contrary, the late MCA (1200 - 1300 CE), shows relatively cooler and stormy winters and warmer spring-falls (Fig. 5).

Deleted:

At present, precipitation occurs mainly as a result of the moisture carried by westerly winds that become predominant during NAO negative phases (Trigo et al., 2004). However, Yang and Myers (2007) have proposed that persistent positive NAO conditions have also generated strong heat and moist transport from the Atlantic.

A clear relationship between the NAO-derived atmospheric circulation over Europe and the decadal variability of north Atlantic surface temperatures (AMO), with northerly winds over Europe associated to a positive state of the AMO and zonal winds to its negative state has been shown by Yamamoto and Palter (2016). But, the clear imprint of AMO variability on European summer temperatures is not observed during wintertime. An absence attributed to a cancelation of the ocean SST expression by strong cold winds (Yamamoto and Palter, 2016).

Previous work from the Iberian/Atlantic ocean region (Abrantes et al, 2011) suggests coherence between SST at Porto and the instrumentally and tree-ring reconstructed AMO implying a connection between the Iberian Peninsula coastal circulation and multidecadal variability of North Atlantic Ocean SSTs (Gray et al., 2004; Mann et al., 2010).

Frankcombe et al. (2010), propose that the AMO is dominated by two main time scales: 20-30 yr associated with the AMOC and so, of ocean internal origin, and 50-70 yr related to the atmospheric exchange between the Atlantic and the Arctic Ocean. More recently, Buckley and Marshall (2016), revised the periodicities shown by various instrumental and proxy records, and grouped them into decadal (20 yr) and multidecadal (± 40-70 yr), and show statistical significance for the 70 yr periodicity, supporting that ocean dynamics play a significant role in the variability of the European climate on multi-decadal time scales (Yamamoto and Palter, 2016; Zhang, 2007).

To investigate the influence of the (AMO) on the weather regime over the Atlantic Iberian Peninsula, we performed wavelet analysis on our SST and [n-alk] records (Figs. 6, 7). Results reveal a 74 yr periodicity for SST and precipitation on the west coast mainly before 1300 CE and in the south coast after 1580 CE. In addition, longer period processes (100 – 180 yr) are found throughout the 3 SST records and before 1200 CE in the precipitation stack (256 yr). If our wavelet results are interpreted in the light of the above-presented information, multi-decadal variability of the North Atlantic dynamics associated with the Atlantic and Arctic Ocean exchange, has an important impact on SST and precipitation over the Atlantic sector of the Iberian Peninsula, mainly between 900 and 1200 CE in the north and after 1580 CE in the Algarve.

However, to explain the occurrence of big storms clustered in the early MCA on the Northwestern Iberian Peninsula, the modern path of westerly winds under NAO positive conditions would have to be positioned southward of 41ºN, a shift that could have been caused by an increase in mid-latitude blocking anticyclones.

Considering that: (1) SCAND is related to major blocking anticyclones over Scandinavia and has a positive mode associated with above-average precipitation across southern Europe (Comas-Bru and McDermott, 2014; Jerez and Trigo, 2013); (2) the negative relation observed between NAO and precipitation in winter, and the EA and SCAND positive relation to winter precipitation in the Northern Iberian Peninsula; and (3) the slight positive relation of SCAND with precipitation in the north but important negative effect in temperature in the southern Iberian Peninsula in summer (Hernández et al., 2015). One possible explanation for the observed strong precipitation in the north and lower SST in the Algarve during the early MCA may be the effect of a positive SCAND (Fig. 5).

In summary, the interplay between North Atlantic multi-decadal variability associated with the Atlantic and Arctic Ocean exchange and the positive modes of the NAO, EA and SCAND, are inferred to explain extreme precipitation associated with warm winters and cool summers observed in the Iberian Peninsula during the early MCA. On the contrary the cold stormy winters and warm summers of the late MCA are attributed to a shift in the SCAND to a negative mode.

5.2.2 The warming of the Industrial Era: atmospheric forcing and oceanographic circulation changes

The transition to the Industrial Era starts at 1750−1850 CE with an increase of SSTs to values similar to those detected prior to 1300 CE in all but the Porto record (Figs. 2A, 5) (Abrantes et al., 2011). The same warming is detectable in all the AP pollen records (Fig. 4B); a pattern that coincides with the atmospheric temperature rise detected in NE Spain, Europe and the Northern Hemisphere (Luterbacher et al., 2016; Martín-Chivelet et al., 2011; Moberg et al., 2005) (Fig. 2D, E, F).

In contrast the SST stack anomaly curve shows a smooth signal when compared to the SST data during the same time frame (Fig. 2A, B). Indeed, the Porto and Algarve records show opposite SST patterns that cancel out and result in a leveled SST in the Stack (Figs. 2A, 2B, 5). Superimposed on the 20th century trend are decadal-scale oscillations of unusually large amplitude but an inverse signal is detected for SST and river input in the Algarve (Fig. 2A, 5). Of particular note is the second rise of SST by the mid 20th century (± 1970) (Fig. 2A), which coincides with the highest global temperatures of the last 1,400 yr (Ahmed et al., 2013) and agrees with a second warming phase in the Western Mediterranean (Lionello et al., 2006).

Zampieri et al. (2016) proposed that the rapid warming periods of the Northern Hemisphere, including the last one in the '90s, are mainly modulated by shifts in the AMO from negative (cold) to positive (warm) phases. A close look to the AMO index records of Gray et al. (2004) and Mann et al. (2010) (Fig. 2H), reveals that both warming steps (1850 and 1970 CE) do indeed occur during warming transitions in the AMO index, supporting the notion of a stronger influence of the North Atlantic SST pattern on southern Iberian climate as found for the central-western Mediterranean Sea (Cisneros et al., 2016).

In the Algarve, the highest SSTs are likely to reflect the warm inner-shelf counter-current associated with large-scale northerly winds during the upwelling season (Garel et al., 2016), which in turn are known to have registered a substantial intensification during the peak summer months (July to September), in the last 50 yr in SW Iberia (Relvas et al., 2009).

Furthermore, the occurrence of periods of strong precipitation when SST is low, appear to be related with the change from a negative mode of the EA between 1900 – 1970, to a positive EA after 1970, while NAO and SCAND remain positive (Fig. 5; NOAA historical archive and indices - http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml; and http://www.cgd.ucar.edu/cas/jhurrell/)

In summary, the mid 20th century rise in SST in the Algarve emerges as a regional response to the unequivocally warming of the global ocean since the 1960's (IPCC, 2013b). The reverse trend registered at the Porto site compared to the southern records, clearly demonstrates the regional differences that are likely to result from global warming via the complexities of the regional ocean dynamics (Seidov et al., 2017).

Considering the high relevance of such environmental changes to ecosystems organization and sustainability, a more in depth discussion of its effect at the regional scale is necessary.

6 Conclusions

The combination of SST and terrestrial input/river discharge records from five sites distributed along the Iberian margin (36º to 42 ºN), captures the spatial distribution of temperature as well as continental precipitation for the last 2,000 yr on different time scales. Furthermore, the new regional stacks for SST and [n-alk] provide a meaningful form to understand the role of global/hemispheric vs regional variability.

Orbital-scale summer insolation imposes long-term cooling from 0 CE to the beginning of the 20th century, at all latitudes with maximum amplitude at the southern sites. Century/decadal scale climate changes follow the overall climatic patterns of the extra-tropical Northern Hemisphere and Europe. The RP and the DA climate records are explained by the mechanisms proposed by Sánchez-Lopez et al., (2015), MCA shows two climate phases: the early MCA (900-1100 CE) with warm winters, cool summers and extreme flooding imply a link between AMO and a high pressure blocking system over Northwestern Europe (positive-like mode of the SCAND) as well as NAO and EA on a positive phase; the late MCA (1200-1300 CE) cold stormy winters and warm summers suggest a shift in SCAND to a negative mode..

The LIA is marked by the coldest SSTs and frequent but not extreme storms attributed to a dominant negative NAO and EA modes. The Industrial Era starts by 1800 CE and is marked with a SST rise in consonance with increasing influence from the internal North Atlantic ocean variability on the Atlantic Iberian Peninsula climate. A second increase in SST at ± 1970 CE is particularly marked at the Algarve site as a regional imprint of the global warming impact previously simulated for southern Iberia.

7. Team list

8. Copyright statement

9. Code availability

10. Data availability

Primary data for the new sedimentary sequences is archived in PANGEA (doi: 10.1594/PANGAEA.882269).

11. Appendices

12. Author contribution

Abrantes, F – PI of the various projects that funded all the data combined in this paper, had the idea and wrote the paper;

Rodrigues, T– Responsible for the biomarkers analysis in all cores;

Rufino, M – Statistical data analysis;

Naughton, F – Responsible for the pollen interpretation and age-models of DIVA and POPEI;

Salgueiro, E – Data of GeoB11033-1 core;

Oliveira, D – Pollen analysis of the DIVA core;

Domingues, S – Pollen analysis for the Tejo site D13882 and POPEI core;

Costa, A. – Age-model for core GeoB11033-1;

Oliveira, P – Processed the satellite-derived and OISST data;

Drago, T – Provided the Algarve core (POPEI);

Mil-Homens, M – Participated in the DIVA cruise;

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Figure 7 – The continuous wavelet power spectrum of the [n-alk] Stack record (A); the north [n-alk] Stack (B) and the Algarve [n-alk] record (C). The thick black contour designates the 95% confidence level and the lighter shaded area represents the cone of influence (COI) where edge effects might distort the results.

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