Dear Referee #1,

Thank you very much for your comments on our manuscript. Please find below some replies to your comments.

Comment: I think for a special issue dedicated to 4.2 ka event, it would be useful to expand the discussion on this point.
Reply: We agree that the discussion on the actual 4.2 ka event is short. We did not want to put the discussion of the 4.2 ka event in the centre of the manuscript since the events observed at ca. 5.0 ka and 3.8 ka seem to be much more pronounced in our records. Nonetheless, a more detailed discussion on the timing of the 4.2 ka event in our records has been added.

Comment: Sometimes the text contains statements about good agreement between different proxies and archives while in some instances differences are recognized.
Reply: We computed correlation analysis (Pearson) with our records underscoring the good agreement in general. Moreover, the differences, which occur, are more critically discussed.

Comment: Probably it would be useful to plot in figure 2 also the older ages model. In a way that older records will not be any more selected if not recalculated on the new age models.
Reply: We agree. The previous age model of Jiménez-Amat and Zahn (2015) has been indicated with a dotted line in Figure 2.

Comment: Pag. 2 line 6: mean primary productivity (MPP), it is the first time quoted in the text.
Reply: You probably refer to line 26. Please note that MPP is already introduced in line 24.

Comment: Pag. 3 line 2, delete regime after Mediterranean
Reply: 'regime' has been deleted.

Comment: Pag. 3 line 7 mm instead of ml
Reply: 'mm' has been written instead of 'ml'

Comment: Pag. 3 line 14 delete during winter (written twice)
Reply: the second 'winter' has been deleted

Comment: Pag. 4 line 14 why you don't refer to Reimer et al. 2015? Pag. 4 lines 18-19 linearly interpolated.....be more precise which ages are interpolated.
Reply: Also following Referee #4 comments we used Bayesian Modelling to construct our age model. Accordingly, the whole chapter has been re-written, but we now referred to Reimer et al. (2013) mentioning the marine13 calibration curve and the 400 yr reservoir correction. We hope that Referee #1 intentionally meant this paper, because we are not aware of any paper from Reimer et al. in 2015.

Comment: Pag. 6 line 2, 10 ccm? Do you mean 10 cm? or?
Reply: We meant 'cubic centimetres' and adjusted it towards 'cm^3'.

Comment: Pag. 6 line 13 Proxy restrictions? What do you mean precisely?
Reply: With 'restrictions' we mean the (spatial, temporal, etc.) limits of the used proxies. But we re-structured also this chapter and included it into the discussion.

Comment: Pag. 6 line 17 Jalali et al. 2016, 2017 Pag. 6 line 23 Vogts et al.,2009,2012
Reply: Thanks, we adjusted this. Unfortunately, this was a formatting problem with the citation software.

Comment: Pag. 7 line 18 how changes of 1◦C are significant considering the accuracy of the methods?
Reply: Of course, these changes are not significant because they are within the methodological error. To emphasize this, we inserted a statement that these SST changes need to be considered with caution. Additionally, we have added an error bar indicating the methodological error within Figure 3.

Comment: Pag. 7 line 20 "Annual mean SST in GeoB5901-2 vary stable? Is very stable around ca. 20.0◦C? It would be useful to give numbers as mean±sd. This can give also an idea of significant deviation from the mean.
Reply: We followed this suggestion.

Comment: Pag. 8 line 11 ....well matches....later you wrote it is not always the case. It is better to write some like "there is a general agreement. and Pag. 9 line 15 "drought episodes are paralleled" I think once again caution is necessary and description of mismatching is necessary.
Reply: You are right. We computed correlation factors (Pearson) also referring to a comment from Referee #3 in order to statistically support our statements.

Comment: Pag. 9 lines 26-26. How is it possible that insolation decrease and SSt increase? Is there any wrong in this sentence? Or a further explanation is necessary? Which temperature are really recording your proxy? It probably needs some explanation.
Reply: Sorry this was a mistake. We meant that over the Holocene SSTs are generally cooling (due to decreasing insolation) with lowest SSTs (in the mean) during the present. Consequently, it is reasonable that the SST in the Mid- Holocene was warmer compared to modern temperatures. We corrected this mistake.

Comment: End pag. 9 beginning pag. 9. Please check carefully. It is little confusing and it is not always evident to understand which SST you are referring to (mean, seasonal).
Reply: We agree that this is a little confusing and difficult to read. We re-structured the discussion chapter into terrestrial and marine sub-chapters and discuss the annual, winter and, summer SSTs more separately within the marine sub-chapter.

Comment: Pag. 10 lines around 15, some further, more explicit comment on what temperature are measuring with your proxies is necessary.
Reply: Comparing the Gulf of Cadiz alkenone (annual mean) SST with other data, we wrote: "*The here reconstructed annual mean SSTs appear actually more close to summer conditions*". To be more specific a more detailed discussion on this issue has been added.

Comment: Pag. 10 lines 19-21. I don't think second decimal can be considered significant considering the age model.
Reply: We aimed to delete every second decimal before submission, but obviously we must have missed those numbers. This has been changed.

Comment: Pag. 10 lines 21-21. "These events, notably, differ from...." Surely this part needs to be expanded a little more.....
Reply: We agree. Some additional sentences for explanation and discussion on this point were added.

Comment: Pag. 10 I have no particular problem about the selection of Goslin et al. 2018 record, but there are also others. Is there any special reason? Is this record better dated? More robust?

Reply: We followed the comment of Referee #4 and compared our data to the NAO reconstruction of Olsen et al. (2012). Initially, we chose the Goslin et al. (2018) record because it covers the whole time interval (until 5.5 ka BP), while the NAO-reconstruction from Olsen et al. (2012) ends at 5.2 ka BP.

Dear Referee #2,

Thank you very much for your comments! Please find some replies below.

Comment: The text is mostly well written but lacks an into detail comparison to other records of the region as well as a detailed description of and introduction to the ocean currents around the Strait of Gibraltar and their evolution, which might be of great value related to the topic of the study.
Reply: We agree. A more detailed comparison to key references such as El Refugio Cave as well as an introduction and discussion on the ocean currents has been added.

Comment: I am not convinced of the title, not about the "multi-decadal", nor about "southern Iberia". SST, maybe as well as Alboran sea and Gulf of Cadiz or oceanic variability should somehow be included in the title.
Reply: We think that the temporal resolution of our records is allowing multi-decadal resolution and is one of the key features of this study. Thus, we want to highlight this also in the title. However, Referee #2 is right with his comment that we do not resolve seasonal variations on multi-decadal resolution. "Southern Iberia" is the region the terrestrial plant proxies stem from and as our study is very local also with respect to the oceanic proxies we should keep this phrase. Nonetheless, we agree that the title so far excludes the oceanic regions, so we will include a "atmospheric and oceanic climate variability" in the title.

Comment: Section 1.1, line 5: mentioning of that figure is wrong, a precipitation curve would show the precipitation during winter
Reply: Correct! We have included a precipitation and atmospheric temperature curve in Figure 1.

Comment: e.g. Line 6: would be nice to see the Atlantic regime within the figure. Btw, you use ml in the text and mm as unit for precipitation in the figure, can you adjust that?
Reply: The regimes can be defined by the precipitation amount, therefore in a way it is already shown. Drawing an additional line etc. to our opinion would result in a too busy figure. The units have been adjusted.

Comment: Line 14: you mention again figure one, to my opinion in the wrong sentence.
Reply: Figure 1 has been adjusted so that winter precipitation (October to February) is shown. We think referring to Figure 1 is correct in this sentence.

Comment: Concerning figure 1: (a) the figure shows too much of the Iberian Peninsula, you can easily reduce the area you show and exclude the Ejulve cave. A north arrow or coordinates are missing as well as a scale. The river beds could be shown more clearly. And I would not call the red shaded area the Alboran sea catchment, as a catchment should be related to the input area rather than the endmember of the area affected by the rivers (e.g. you call the other catchment Guadalquivir catchment, not Gulf of Cadiz catchment). I would also not use alphabetic letters for the discussed references, as it is difficult to read and find them within the caption, if you use a, b, c already for the subdivision of figure 1. January should not be written with capital letter in the caption. (b) and (c)

could also be completed by coordinates or a north arrow and a scale. What are the white spots within (b) and (c)?
Reply: Thanks a lot to Referee #2 for these helpful comments on Figure 1. Much of these have been adjusted! We think we should not reduce the size of the map by cutting off the northern part, because we want to highlight that the modern true moist Atlantic regime is far to the north while the area under consideration is a much dryer system. North arrow, scale and, coordinates have been added. We also tried to make the river beds more visual by adding a shading to the river bed. "Alboran Sea catchment" has been renamed to "catchments from various small-scale rivers draining the southern Sierra Nevada". The naming of the catchments was also moved from the Figure into the figure caption. We agreed to differentiate between "shown" and "mentioned" sites because otherwise, we might imply wrong expectations to the reader. For that purpose, we used numbers and small letters for separation. We will keep this because capital letters, for example, would highlight these references too much. Furthermore, the use of small letters for figure subdivision is wanted by the journal. But, we think that in the final manuscript the small letters used for subdivision of the Figure 1 will be shown in bold, so that they should be easier to distinguish. As already said "January" has been replaced by "winter" anyway. The respective months are mentioned in addition. The white spots in subfigures (b) and (c) -now (c) and (d)- are mapping gaps. These are mainly occurring in coastal areas as well as in case of lakes. In order to remove some of the white spots we now show the elevation on land instead of continent in grey.

Comment: Section 2, line 25: resampled on 0,5 cm is not wright, as you mention every second centimetre in line one of page 4. Section 2.2,
Reply: We agreed that the description is difficult to read. We adjusted that in the following way: "*Sediment core ODP-161-976A (36°12.32' N; 4°18.76' W; 1108 m water depth) was retrieved in the Alboran Sea during JOIDES Resolution cruise in 1995 (Comas et al., 1996). To achieve multi-decadal resolution, the section from 100.0 cm to 149.0 cm was continuously sampled at 0.5 cm distances in the IODP Core Repository at MARUM in Bremen (Germany)."* For simplification we do not mention the two different sampling steps, which are the reason for the different temporal resolution of the geochemical and foraminiferal data.

Comment: Age model: line 19, 20: can you interpret the sedimentation rates by the use of other studies? Figure 2: why the abrupt steps of the sedimentation rate of ODP and smooth increases and decreases of GEOB? Figure caption is very long, could you include the naming of the record within the figure next to the line?
Reply: Unfortunately, comparable cores (timing, sampling resolution, location) are very scarce (see discussion of the oceanic variability) not allowing the comparison of sedimentation rates. Moreover, the interpretation of sedimentation rates –especially without any reference data- is difficult and beyond the scope of this study. Following a comment from Referee #4, we used Bayesian modelling to create the age models, which also resulted in more smoothed sedimentation rates except for one abrupt change in each sediment core. We re-wrote the figure caption and included the names of the sediment cores into the Figure.

Comment: Line 15: what is the reason for that massive shift? Can you explain that?
Reply: So far, we cannot decide whether the previous dates are "wrong" or "right". A measurement at the same sampling depths would be needed to do so, but this is impossible since these samples do not exist anymore. We assume that the shift is probably a consequence of a sampling of a much larger depth increment for dating by the previous studies.

Comment: Line 16, 17: the exclusions of the ages that you have is not really explained and the reason of lowest analytical error is not enough. Can you explain the "errors" in greater detail, where they might come from etc?
Reply: The errors are the methodological error from the dating itself and the calibration curve of course. Following Referee #4 we modelled the age model using a Bayesian approach (see comment above). Doing so, we kept all double-dated samples. For the new age model, we just excluded two AMS dates at 116.25 and 124.75 cm, because we assume a rather smooth and constant sedimentation rate. This is because there are no evidences for bioturbation etc. resulting in a 10 cm thick section of similar age. Since the sample at 120.25 cm is also double-dated we just kept this date. This explanation has been added in the revised version.

Comment: Section3, results: you do not include cal after the naming of an age, this is not consistent with the legends of the axes of the figures.
Reply: This is true! We have adjusted that.

Comment: Section 2.3: why abbreviation of methanol MeOH? Looks like a molecular formula, which would be CH4O..
Reply: Correct! We deleted this lab-internal abbreviation since it is not used somewhere else in the text.

Comment: Page 7, Line 2: mentioning of figure 1 is not necessary.
Reply: We deleted the hint to Figure 1 here.

Comment: Page 8: line 7 and 8 is too my opinion exaggerated.
Reply: We have deleted this sentence.

Comment: Page 8, section 4,line 21+22: references are missing and included with more detailed information in line 1,2 and 3 on page 9, which could be included in page 8, line 21.
Reply: This was meant to be an introductory sentence for the following discussion, but we deleted it.

Comment: Line 7 on page 8, rephrase "moreover, a forest ..." as it is unclear.
Reply: We rephrased this sentence to *"Furthermore, a drastic forest opening in SE Iberia is indicated from the Elx pollen sequence at ca. 4.3 cal. ka BP and at Cabo de Gata around 4.4 cal. ka BP (**Figure 6**; Burjachs and Expósito, 2015)".*

Comment: Line 15, drought episodes parallel to Norm 33... I don't think so!
Reply: The term "all" is replaced by "most" since we agree that in ODP-161-976A the last two periods of drought at ca. 3.8 and 4.3 ka BP are not accompanied by clear Norm33 peaks.

Comment: Line 23, where can I see that in figure 3?
Reply: We deleted the reference to Figure 3 here.

Comment: Page 11, line 15, why is there no explanation why bond 2 is not visible?
Reply: We agree. A critical and detailed discussion on Bond Event 2 has been added.

Comment: Figure 6: not really discussed within the text.
Reply: We have added a more detailed discussion on the mechanism proposed by Figure 6 and, more general, thriving the oceanic variability in relation to the Bond Events.

Comment: Section 5: the conclusion should be rephrased and maybe restructured too, some bullet points of your study, what is the most important interpretation etc.
Reply: We rephrased the "conlusion" trying to focus more on the most important outcomes of our study.

Dear Referee #3,

Thank you very much for your inspiring and helpful comments. Please find some replies below.

Comment: The introduction seems to focus mainly on the 4.2ka event where the data set and the remainder of the paper is much broader than that one event. I would like to see an extension of the introduction to cover more of the mid-late Holocene "events" in detail. The introduction could also include more background on the major forcing mechanisms in play here and discussed later in the paper. The NAO bit is in the study area section, but there is no info on the Bond events, and how these may influence ocean circulation and SST's in this region.
Reply: A true point. We restructured the introduction also explaining the NAO and the Bond Events in general. Nonetheless the focus on the 4.2 ka event as an example remained since we also followed the suggestion of Referee #1 and concentrate more on the 4.2 ka event in the discussion.

Comment: Figure 1 needs improvement. A scale, north arrow and labelling of the different oceans, countries etc is needed for a non local expert reader.
Reply: We have implemented a scale as well as a north arrow. Labelling of the Atlantic Ocean and Mediterranean Sea as well as the sub-basins such as the Gulf of Cadiz and the Alboran Sea is now included. We won't label countries for political reasons. Also the journal encourages us not to do so.

Comment: It would be nice to see the sedimentation rates through time plotted in your figures (Figure 3 for example) this would help get a feeling of how the different cores were deposited over time and will help inform the reader with regards to sample density vs time and therefore resolution of the data set. This is critical when interpreting changes at the multi-decadal level.
Reply: A very good point! We moved the sedimentation rates from Figure 2 to Figure 3.

Comment: You state that two dates were removed (page 4 line 17) as they gave the same value as another date at 120cm. Can you explain why they were removed? Does this not just suggest a rapid accumulation rate over this period of the core and that all dates are valid?
Reply: We extended the discussion on the age model and explain the removal of particular dates in more detail. Considering these two dates as evidence for an extraordinary high accumulation interval is ruled out, because in the sediment core itself there is no evidence by any lithological feature, grain-size or other properties for such anomaly. In the meantime, we also followed the suggestion of Referee #4 and modelled the age models using a Bayesian approach, that allows to better consider the reliability of these dates.

Comment: I have some concerns about the use of the n-alkane data as the primary proxy for wetter or dryer conditions; I fear this proxy has been over extended in the interpretation. The areas I would like clarification are: a) it would be nice to see a couple of example chromatograms from the n-alkane work, especially during the extreme wet and dry periods (supplementary info is appropriate). This would help clarify if the material is originating from the same/similar source locations throughout the record. My concern is that over such a large catchment and long time period, changes in rainfall may be geographically heterogeneous, leading to the removal of organic matter from different parts of the catchment at different rates over time.

Reply: We included example chromatograms in the supplement and additionally collected information on the vegetation of the catchment areas in order to assess this point.

Comment: b) Linked to this, more explanation of the physical mechanism of n-alkane removal by runoff is required (at least in your response to these comments). I'm concerned that under dry conditions, C3 dominated environments (forests for example) are less susceptible to water and sediment loss than C4 dominated environments, due to the physical make-up and bonding of their soils by root systems. If this is the case then the co-variation between n-alkane concentration reduction and "C4 proxy increase" is actually not showing an increase in C4 vegetation abundance within the catchment, but a change in the relative loss of n-alkanes from each environment within the catchment. c) I would also direct the authors to the following paper, which suggests that identifying between C3 and C4 vegetation using n-alkanes is not straightforward, this needs consideration and clarification. Bush and McInerney (2013) Leaf wax n-alkane distributions in and across modern plants: Implications for paleoecology and chemotaxonomy. Geochimica et Cosmochimica Acta 117 (2013) 161–179.
Reply: We added a few sentences on the physical mechanisms in the discussion. Moreover, according to Short Report #1 the interpretation concerning the vegetation shifts will be less strong in the revised version. A large scale shift from C3 to C4 vegetation is not considered anymore, which would also reduce the concern expressed by Referee #3.

Comment: d) How can you be sure that reductions in the n-alkaline concentration in the core are not just a dilution effect from marine sediment deposition? Showing sediment accumulation rate on the same graph would clarify this (see comment above).
Reply: The sedimentation rate is plotted in Figure 3 to allow comparison (see reply above). Also we added a small discussion on whether the sedimentation rate affected the used proxies or not.

Comment: There are a few places in the text where you suggest this are "well correlated" or that events are well replicated in both cores (page 7 line11, page 8 line 11, page 10 line 7). I think the paper would benefit greatly from some stats to back up these statements, which are currently based on a visual assessment of the data. Being able to demonstrate a relationship between the cores will greatly enhance the robustness of the conclusions drawn.
Reply: We fully agree. We now calculated Pearson's correlation coefficients for compared data. A detailed description of how this has been done has been added to the supplement.

Comment: I would also suggest that you investigate the periodicity of the wet-dry events shown in the record. NAO and bond events have well documented "frequencies", if you can demonstrate that these events in your record have a similar frequency this would again add weight to the argument that these major climate modes maybe the dominant mechanism controlling changes seen in your record.
Reply: We tried to apply spectral analysis to the proxy records. Unfortunately, the analysed time period is too short for producing robust results, at least for the ca. 1500-year Bond cycle. Therefore, we refrain from applying this approach and have to limit the discussion on visual correlation.

Comment: If you are confident that the Norm33 does represent changes in C3-C4 vegetation distribution within the catchment (see comments above), I direct you to page 9 where you suggest that changes in vegetation community composition may change on very rapid time scales and that this can be accurately recorded within the ocean records. Under modern conditions, is there evidence of changes between C3 and C4 vegetation makeup over the time scales you see in the sediments? And, could you use these proxies to quantify the extent of vegetation change that would have been seen to get such a change in Norm33. What I'm asking I guess is, does the extent of Norm33 change seen in the record make sense, in terms of both rate of change from C3-C4 and the extent (%) of vegetation cover that would have to have changed, if contextualised by our understanding of the catchment under modern conditions?

Reply: As stated above the interpretation concerning C3-C4 vegetation change has been discarded.

Comment: The SST data resolved from alkenone data is interesting but it must be clear within the text (when interpreting) and within the figures when this data falls within the 1◦C error that you state in the methods (I suggest adding error bands in the figures). For example, in Figure 3 most of the peaks and troughs in your seasonal SST data are within error. This data is best interpreted in terms of differences between season temperatures (which you do well). Don't over interpret unless the max/min temps fall outside your (+/-?) 1◦C error.
Reply: We added a statement on the SST error in the discussion chapter and in order to visualize the error in the figures we plotted a single error bar displaying the mean analytical and/or methodological error. Unfortunately, the plotting of error bands, as suggested by Referee #3 would results in too busy figures, which would hamper the visual correlation.

Comment: I think that more detail on the significance of not seeing Bond event 2 should be added. You suggest this is the first time higher seasonality in SST in relation to mid Holocene Bond events is described this far south. More mechanistic detail of how this N Atlantic process effects the Gulf of Cadiz would be helpful in understanding why there are difference between the mid and late Holocene Bond events and how it shows up at your sites.
Reply: We agree. We extended the discussion on the Bond Events and associated mechanisms.

Comment: Page 3 line 14, "during winter" repeated.
Reply: This has been adjusted.

Comment: Page 6 line 1, "cm" not "ccm"
Reply: It has been changed to "cm^3" since we meant cubic centimetres.

Comment: Page 7 lines 1 and 2, use "in high resolution" not "on high resolution".
Reply: This has been changed.

Comment: Page 10 line 8, Figure 6 is introduced into the text before Figure 5, re-order figures.
Reply: Figures 5 and 6 have been completely re-structured.

Dear Referee #4,

Thank you very much for your helpful comments! Please find replies below.

Comment: 1) Chronology and resolution. While it is claimed that the records have high-resolution, this is not evident from the data. It is not clear how many samples have been analyzed, especially for core 976A and what was the resolution: 0.5, 2 cm? Further, the choice for excluding several of the data points from the final age-depth model seem to be arbitrary – the exclusion of the ages with lower precision lead to further exclusions. How would the age-depth model have been if the samples with the lower precision were kept, instead (±10 years at 4000 cal BP does not make a big difference). Further, the choice of linear interpolation has been shown to give less reliable ages (Blaauw et al., 2018). Why not using Bayesian modeling?
Reply: The comments on the chronology and resolution are greatly acknowledged! We have added a clear statement that the sampling resolution is 0.5 cm. Moreover, we followed the suggestion and used Bayesian modelling in order to construct our age model. Thereby, we kept the double dated samples (the ones formerly excluded due to lower precision) and just neglected two dates. The

exclusion of these two dates is now explained on the basis of the lithology of the sediment core, which provides no evidence for an extraordinary high accumulation interval.

Comment: 2) The "results" and "discussions" chapters should be better separated, some of the text under the later would better fit under the former.
Reply: We have shifted the comparison of our records into the "results" chapter.

Comment: 3) Their seem to be multiple issues with the "alignment" of the proxies, possibly resulting form the less precise (see above) chronology. Which of the several periods is identified precisely with the 4.2ka event? Further, given that both summer and winter temperatures are reconstructed, the discussion should be separated for the two seasons. Next, rather than assuming that the 4.2 ka event was dry in the region and try to support this by choosing one or other of the "peaks" in the data I suggest starting with multiple hypothesis and discuss them in light of your data. Several studies in the wider study region have shown that the 4.2 ka BP event could have ben wet (e.g., Zielhofer et al., 2018) during winter.
Reply: For the "alignment" of the proxies we now used statistical methods (Pearson's correlation coefficient) to underline our interpretation. Also following Referee #1, we have emphasized the discussion on the 4.2 ka event. Thereby, we followed the suggestion of Referee #4 and started with multiple hypothesis. Furthermore, to improve the readability we divided the discussion on the SSTs for summer and winter season also following a comment from Referee #1.

Comment: 4) The mechanisms described in chapter 4.2 ("Possible drivers...) rely more on Ausin et al. (2015) than on the data from the power. See also the comment above and the detailed comments below and try to improve the interpretation by providing a mechanistic evidence for the described processes.
Reply: We increased the discussion on the driving mechanisms also providing more detailed ideas on how they work and can affect our data.

Comment: P1, L23: Dansgaard et al (1993) is outdated, perhaps some newer and better references would be better
Reply: We replaced Dansgaard et al. (1993) by Rasmussen et al. (2014).

Comment: P2, L2: numerous other events are not resolved in NGRIP...
Reply: We have deleted this reference.

Comment: P2, L12-13. I am not an archaeologist/historian, but perhaps "turnover" is not the best word to be used in this context
Reply: This part of the introduction has been deleted. Following Referee #3 we wanted to minimize the focus on the 4.2 ka event in the introduction. The introduction now focusses just on the climate and the mechanisms considered as possible driver.

Comment: P2, L20. Please detail the contrast
Reply: We added some examples for this contrast.

Comment: P3. The word "relatively' is overused in the chapter 1.1. While Iberia is relatively cool (L2) compared to N Africa, is relatively hot, compared to N Canada. Please give the values for the temperature, it would allow readers to better understand the present-day climatic conditions.
Reply: We added modern values for temperatures discussed in this chapter.

Comment: P3, L7 you mean mm instead of ml
Reply: We have corrected this.

Comment: P3, L15: please detail the circulation, separately for the season, it is not clear from the text (e.g., you discuss low SST in the Atlantic margin and than jump to warm inflow to the Alborean Sea...)
Reply: We added a detailed discussion on the ocean circulation also separated for summer and winter season. The oceanic currents and circulation pathways have also been drawn into Figure 1.

Comment: Materials and methods: please improve the description of the sampling strategy, it is not clear what resolution you achieved in the end. Age model: see the comments above, the choices need to be better explained. A critical discussion on how a different choice of exclusions would have affected the results would be welcomed.
Reply: We re-wrote these chapters (see reply above).

Comment: P6, l1: ccm is cm3?
Reply: Yes, it should be. We have adjusted it.

Comment: P6, proxy reconstructions. Please give values for the Q for both rivers, as well as for the seasonal discharges to better understand the seasonality of alkanes in the cores
Reply: We added seasonal discharge data for the Guadalquivir into the "study area" section. Unfortunately, we did not find such data for any rivers draining the southern Sierra Nevada. All we found were very recent data, which are affected by river dams and, thus, show a very different anthropogenic signal.

Comment: P7, results: please ad "cal" after ka (e.g., 4.3 ka cal BP)
Reply: We have adjusted this for the whole manuscript.

Comment: P7, L11: the contemporaneity should be discussed in the light of chronological issues; P7 and 8, results: the entire chapter is somewhat confusing, please try to simplify it. Also, it is not clear how the various dry/cold/warm periods have been found to be contemporaneous.
Reply: We re-structured the "results"-chapter and separated it for both sediment cores – each with a clear separation of terrestrial and oceanic proxy results. Afterwards, we added a sub-chapter comparing the data of both sediment cores using also statistical approaches (see reply above) and also discussing chronological issues.

Comment: P8, l19: was it dry in winter or summer? See the detailed comment above
Reply: It was most likely dry in winter since our n-alkane proxy is probably biased towards the winter season. But, we have added this also in the discussion when discussing our n-alkane data.

Comment: P9, L11: 20 years..what is the age error here?
Reply: We deleted every second decimal within the ages. Also, according to the new age model this period is now longer. Furthermore, we gave the age uncertainty for every dry event observed in our study.

Comment: P9, L15: winter or summer, again? Generally (I repeat myself) the discussion should be clearly separated for summer and winter

Reply: We agree that this was confusing and difficult to read. We re-structured the discussion chapter into terrestrial and marine sub-chapters and, further, discussed the seasonal SST variations separately.

Comment: P9, L25-26: not clear, the cooling trend would result in colder, not warmer SSTs
Reply: We meant that over the Holocene SSTs are generally cooling (due to decreasing insolation) with lowest mean SSTs during more recent times. Consequently, it is reasonable that the SST in the Mid- Holocene was warmer compared to today. We have restructured this sentence in order to make this clearer.

Comment: P9, L25: “at that time” What time?
Reply: We replaced “at that time” with “during the studied period”.

Comment: P9, L29 and next lines on P10: for which period are these temperatures given?
Reply: The temperatures mentioned all focus on the studied period between 2.9 and 5.4 ka BP. We have added a clarification in this part.

Comment: P10, L9: hm, the resolution problem. Was it high or low? My quick calculations show that the resolution is closer to 100 years at the time of interest....
Reply: We included the resolution of the “low resolution” studies from the area for better comparison.

Comment: P10, l15-19: for which period does this paragraph refer to?
Reply: For the whole analysed period. We added a statement to make this clear.

Comment: Generally, chapter 4.1 is a mix of results and discussion, most of it should go under “results”
Reply: We have adjusted this (see also reply above).

Comment: P10, chapter 42.. This is the “meat” of the paper, but the discussion is quite weak. I also think that “NAO-like variability” is quite over abused. Further, if the ANO is to be used, perhaps it would be more useful to use a NAO reconstruction, rather than a storminess one, which could result from other factors than NAO (e.g., Olsen et al., 2012)
Reply: We emphasized the discussion on the possible drivers. We also followed the suggestion by Referee #4 and now refer to the NAO reconstruction from Olsen et al. (2012). We, intentionally chose the Goslin et al. (2018) data because it covers the whole time period of our study.

Comment: P11, L15: the comparison with the IRD record is useful as long as the mechanisms linking the two are better described. Else, correlation and causality are different. Please improve the discussion by including mechanistic explanation that could result in the variability described here.
Reply: We introduced the Bond Events and associated changes broadly in the introduction and, further, improved the discussion on the mechanisms in the light of our data.

List of major changes after the reviewing process:

- The interpretation of the Norm33 n-alkane ratio has been revised. Variability is now discussed as result of changes in plant water availability instead of C3 vs. C4 vegetation change.
- The age model of both sediment cores have been modelled using a Bayesian approach instead of linearly interpolating.
- Correlation analysis have been carried out in order to strengthen the inter-proxy comparison/ interpretation.
- The focus of the introduction on the 4.2 ka event was weakened.
- The oceanic currents have been introduced in the "study area" chapter.
- "Results" and "Discussion" chapters have been re-structured to improve the readability.
- A detailed discussion on the 4.2 ka event as well as on the oceanic variability in relation to Bond Events has been added.

Mark up version

Multi-decadal atmospheric and marine climate variability in southern Iberia during the mid- to late- Holocene

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Abstract. To assess the regional multi-decadal to multi-centennial climate variability atalong the southern Iberian Peninsula during the mid- to late- Holocene transition multi-proxy records of twopaleo-environmental indicators from marine sediment coressediments were established for two sites in the Alboran Sea (ODP-161-976A) and the Gulf of Cadiz (GeoB5901-2). High-resolution records of organic geochemical proxiesproperties and planktic foraminiferal assemblages are used to decipher precipitation and vegetation changes as well as the sea surfacehydrological conditions with respect to Sea Surface Temperature (SST) and marine primary productivity (MPP). n-Alkane records asAs a proxy for precipitation changeschange records of plant derived n-alkane composition suggest a series of sixfive distinct drought events dry episodes in southern Iberia at 5.4 ka BP± 0.3, from ca. 5.1 ka BP to 4.9 ka BP± 0.1, from 4.8 to 4.7 ka BP, at 4.6 ka BP± 0.1, from 4.4 to 4.3 ka BP and, from 3.8 to 3.7 ± 0.1 and, at 3.7 ± 0.1 cal. ka BP. During each dry episode the vegetation suffered from reduced water availability. Interestingly, the dry phase from 4.4 to 4.3 ± 0.1 cal. ka BP is followed by a

rapid shift towards wetter conditions revealing a more complex pattern in terms of its timing and duration than was described for the 4.2 ka ~~ka BP. Each drought~~ event ~~is associated with a major vegetation change towards higher proportions of C4 vegetation.~~in other regions. The ~~drought events are further accompanied by annual and spring/ winter SST warming~~ series of dry episodes as well as ~~decreasing MPP~~closely connected hydrological variability in the Alboran Sea~~. Altogether, the close correlation of the observed droughts with~~ were probably driven by North Atlantic Oscillation (NAO)-like variability ~~suggests changes in the atmospheric circulation as important driving mechanism of terrestrial and oceanic variability at southern Iberia and the Alboran Sea, respectively. Sea surface variability in the~~ . In contrast, surface waters in the Gulf of Cadiz~~, instead, is intimately linked~~ appear to ~~the~~have responded more directly to North Atlantic cooling associated with Bond Events. In particular, during Bond Events 3 and 4 a pronounced increase in seasonality with summer warming and winter cooling is found.

1 Introduction

~~The~~ Holocene climate has been considered to be ~~climatically~~ fairly stable in comparison with the large and abrupt climatic changes during the last glacial and deglacial ~~(Dansgaard et al., 1993; Martrat et al., 2007). In the Mediterranean general~~(Martrat et al., 2007; Rasmussen et al., 2014). For the Mediterranean realm, generally long-term trends in Sea Surface Temperature (SST) cooling (Kim et al., 2004; Martrat et al., 2014) and continental aridification (Fletcher and Sánchez Goñi, 2008; Ramos-Román et al., 2018a) are ~~observed during the Holocene. Several climatic events~~ described, superimposed ~~to these long-term trends have been described,~~ several short cold and dry perturbations, for example the 8.2 ka event or the North Atlantic Bond~~-~~ Events (Alley et al., 1997; Bond et al., 1997; Mayewski et al., 2004). ~~Another prominent Holocene climate event – although not well resolved in the Greenland Ice Cores (NGRIP-Members, 2004) – is the 4.2 ka event. This event is considered of global impact with generally cooler and wetter conditions over the North Atlantic, Northern and, Central Europe~~Another prominent Holocene climate perturbation is the 4.2 ka event. This event, considered to have had global impact, is associated with generally colder and wetter conditions over the North Atlantic as well as Northern and Central Europe and is broadly coincident with the onset of Neoglacial glacier advances in Scandinavia and the Alps (Bakke et al., 2010; Le Roy et al., 2017). ~~On the other hand, severe climatic changes in the tropics are described for the 4.2 ka event, for example a weakening of the African, Indian and, Asian monsoonal systems along with sudden changes in El Niño Southern Oscillation frequency (Gasse, 2000; Staubwasser et al., 2003; Toth et al., 2015). Additionally, intense drought events have been described for the mid-latitudes in Northern America and Eurasia including the~~Additionally, intense droughts have been ascribed to this event for the mid-latitudes in Northern America and Eurasia including the Eastern and Central Mediterranean (Booth et al., 2005; Cheng et al., 2015; Jalut et al., 2000; Magny et al., 2013). ~~Consequently, Walker et al. (2012) proposed this event because of its global manifestation as marker separating the Middle to Late Holocene epochs. Just recently, the International Commission on Stratigraphy corroborated this marker with the GSSP being a speleothem from Mawmluh Cave in India (IUGS International Commission on Stratigraphy, 2018).~~

~~The 4.2 ka climatic event is also considered to have significantly influenced the development of ancient societies in the subtropical realm. Especially evidences of sharp cultural turnover coinciding with pronounced drought in the Eastern Mediterranean and Near East gave rise to an array of collapse narratives. In particular, the collapse of the Akkadian Empire and the Old Kingdom in Egypt have been attributed to the 4.2 ka event (Weiss, 2017; Weiss et al., 1993; Welc and Marks, 2014). Also in the Western Mediterranean major social transformations occurred during that time (Blanco-González et al., 2018; Lillios et al., 2016). Yet, the manifestation of this climatic event and, thus,~~

~~potential human responses here remain still unclear. Accordingly, clear evidences of the potential climate constraints and social transformations is still missing, though recently postulated for the western regions of the Iberian Peninsula (Blanco-González et al., 2018). This is partly related to the fact that the 4.2 ka event in the Western Mediterranean is insufficiently resolved in existing marine and terrestrial archives, e.g. several marine archives show contrasting signals, thus preventing sound compilations~~In the Western Mediterranean the 4.2 ka event is so far insufficiently resolved in existing marine and terrestrial archives. Several marine archives reveal even contrasting (dry vs. wet) signals (Weinelt et al., 2015). Concerning terrestrial records, a dry event at 4.2 cal. ka BP is suggested for southern Iberia (Schröder et al., 2018; Walczak et al., 2015) while relatively wet conditions were inferred for northern Morocco (Zielhofer et al., 2018).

Similar to the manifestation of the 4.2 ka event in the Western Mediterranean region, the driving mechanism(s) for it are not well understood. Many studies suggest North Atlantic Oscillation (NAO)-like atmospheric variability as potential driver of climatic change during the mid- to late- Holocene in the area (e.g. Deininger et al., 2017; Wassenburg et al., 2016). The NAO is the dominant driver for the modern precipitation distribution in the Western Mediterranean and particularly active during winter (Hurrell, 1995). Another potential driving mechanism not only of the oceanic variability are the cyclical Bond Events (Bond et al., 1997), which are believed to weaken the thermohaline oceanic circulation and associated northward heat transport, thus, responsible for cooling of the northern hemisphere (Bond et al., 2001; Wanner et al., 2011).

Here, we explore the mid- to late- Holocene climate development in southern Iberia ~~and, thereby, focussing on the potential manifestation and timing of the 4.2 ka event~~ on the basis of two marine sediment cores from the Gulf of Cadiz (GeoB5901-2) and the Alboran Sea (ODP-161-976A). Both sites are analysed for changes in terrestrial vegetation and precipitation ~~change~~ as well as for changes in seasonal and annual SST and marine primary productivity (MPP). For that purpose, ~~we analysed~~ terrestrial n-alkane concentrations and ~~specific ratios, such as~~the Norm33 n-alkane ratio from higher plant leaf-waxes ~~for the terrestrial changes. The alkenone based~~ are used to decipher the continental climate change. For the marine conditions, analyses of the alkenone-derived SST index ($U^{K'}_{37}$) and planktic foraminiferal ~~analyses using~~assemblages applying the Modern Analogue Technique (MAT) were used to reconstruct annual mean and seasonal changes in SST. Changes in MPP are based on fluctuations in the content of alkenones in the bulk sediment. Altogether, this study aims to provide new insights into the temporal and spatial manifestation of the 4.2 ka event as well as ~~alkenone-derived MPP.~~ to discuss potential driving mechanisms by linking terrestrial and marine surface climate variability in southern Iberia and adjacent oceans.

1.1 Study area

The Iberian Peninsula is influenced by ~~two~~the major ~~climatic regimes: the~~ Atlantic and ~~the~~ Mediterranean ~~regime~~atmospheric regimes (Lionello, 2012). Today, the Atlantic climate is typically marked by relatively cool annual air temperatures and evenly distributed precipitation throughout the year. In contrast, the Mediterranean climate is ~~generally~~ characterized by pronounced seasonal contrasts with a rainy winter season and a dry and hot summer season. In general, most of the precipitation at the Iberian Peninsula ~~falls~~occurs during the winter season (Figure 1; Lionello, 2012). The spatial pattern of winter precipitation ~~also~~clearly reflects the two ~~climatic~~atmospheric regimes (Figure 1). The Atlantic regime, which spans along the western and northern coasts, is characterized by high precipitation of more than 800 ~~ml per year. The precipitation falling in the Atlantic climate~~mm during winter. It is associated with the westerly wind belt at the Iberian Peninsula (Zorita et al., 1992) and ~~is~~ to a large extent controlled by the ~~North Atlantic Oscillation (~~NAO~~) during~~ winter conditions (Hernández et al., 2015; Hurrell, 1995). During positive NAO conditions (i.e. ~~a high~~

pressure difference between the Azores High and the Icelandic Low) the North Atlantic storm track and associated precipitation is shifted towards northern Europe, while Iberia experiences more dry conditions. On the other hand, during negative NAO conditions (i.e. a low pressure difference) more storms are directed towards the Iberian Peninsula, which experiences wetter winter conditions.a high pressure difference between the Azores High and the Icelandic Low) North Atlantic storm tracks and associated precipitation are directed towards northern Europe, while Iberia receives less rainfall. On the other hand, during negative NAO conditions (i.e. a low pressure difference) storm tracks are directed towards the Iberian Peninsula, which then experiences wetter winters. The pronounced difference in precipitation is also evident in the seasonal variability of the river discharges in southern Iberia. For example, the average discharge of the Guadalquivir is below about 100 hm^3 per month from April to October and peaks during December and January with values above 400 hm^3 per month (Fernández-Delgado et al., 2007). Nonetheless, the central parts of the Iberian Peninsula as well as the eastern and southern coasts under influence of the Mediterranean climate remain relatively dry on average with precipitation less than 600 ml per year and also during wintermm during winter (Figure 1Figure 1).

The oceanic conditions at the Atlantic margin of the Iberian Peninsula are also characterized by pronounced seasonality. Coastal upwelling along the western continental margin is responsible for relatively low SST during summerA strong seasonal contrast is also evident in the surface ocean in the Gulf of Cadiz, which receives warm waters with the eastward Azores Current (AC) that turns into a poleward surface current (Iberian Poleward Current; IPC) along the western Iberian coast during winter (Peliz et al., 2005). During summer, however, the surface current is directed southward and favours coastal upwelling along the western continental margin limiting the influence of the AC and, thus, causing relatively low SSTs (Figure 1; Haynes et al., 1993). This upwelling system eventually spreads into the Gulf of Cadiz (Haynes et al., 1993). Warm AtlanticHaynes et al., 1993; Peliz et al., 2002). These opposite oceanographic currents limit the seasonality recognized in the SSTs in the Gulf of Cadiz. The seasonal difference at the core location of GeoB5901-2 is typically ~6 °C during modern times (Locarnini et al., 2013). Atlantic surface water passes the Strait of Gibraltar and enters the Alboran Sea. Within the Alboran Sea it circulates in two anti-cyclonic gyres – the West Alboran Gyre (WAG) and the East Alboran Gyre (EAG) (Lionello, 2012). At the western gyreWAG relatively warm and fresh waters become upwelled almost continuously throughout the year (Sarhan et al., 2000). This upwelling is accompanied by an elevated MPP at the northern rim of the gyre (Minas et al., 1991). The modern seasonality in the Alboran Sea is very similar to the one in the Gulf of Cadiz (~6 °C).

2 Materials and methods

2.1 Sediment cores and sampling

For this study two marine sediment cores from the Alboran Sea and the Gulf of Cadiz were analysed. Sediment core ODP-161-976A (36°12.32’ N; 4°18.76’ W; 1108 m water depth) was retrieved in the Alboran Sea during JOIDES ResolutionRESOLUTION cruise in 1995 (Zahn et al., 1999). To achieve multi-decadal resolution, the section from 103.0 cm to 145.0 cm of the working half was continuously sampled at 0.5 cm distances. An extended section from the archive half of this core (100.0 cm to 149.0 cm) was resampled on 0.5 cm resolution in the IODP Core Repository at MARUM in Bremen (Germany) to obtain additional samples for AMS ^{14}C dating and planktic foraminiferal assemblage analysis. Due to an earlier sampling of the archive half, we were just able to sample every second centimetre.(Comas et al., 1996). To achieve multi-decadal resolution, the section from 100.0 cm to 149.0 cm was continuously sampled at 0.5 cm distances in the IODP Core Repository at

MARUM in Bremen (Germany). The analysed section consists of homogenous clayey and silty sediments, which appear slightly bioturbated. No hiatus or depositional event (e.g. turbidite) has been recognized throughout the section (Comas et al., 1996). Sediment core GeoB5901-2 (36°22.80' N; 7°04.28' W; 574 m water depth) was retrieved during METEOR cruise in 1999 in the Gulf of Cadiz (Schott et al., 2000). This sediment core, containing hemipelagic mud, was sampled on 0.5 cm resolution from 1.0 cm to 50.0 cm in the GeoB Core Repository at MARUM in Bremen (Germany). ~~During this study only the section from 12.5 cm to 29.5 cm was analysed. While most of the samples from ODP-161-976A (the ones sampled in 2015) were already available freeze-dried and used for organic geochemical analyses exclusively, samples of sediment core GeoB5901-2 as well as the resampled section from sediment core ODP-161-976A were subsampled for organic geochemical and foraminiferal analyses. The samples used for organic geochemical analysis were subsequently freeze-dried~~The samples used for organic geochemical analysis were freeze-dried and homogenized prior to analysis.

2.2 Age model

Age models of both cores are based on existing and new AMS^{14}C dates, all measured at Leibniz Laboratory at Kiel University (Table 1). Published data of cores ODP-161-976A and GeoB5901-2 were taken from Combourieu Nebout et al. (2002) and Kim et al. (2004), respectively. In addition, we measured six new AMS^{14}C dates on monospecific planktic foraminiferal samples of *Globigerinoides ruber* white + pink or *Globigerina bulloides* larger than 150 µm from sediment core ODP-161-976A as well as seven new dates from sediment core GeoB5901-2. ~~AMS^{14}C data were calibrated and existing data recalibrated using the marine13 calibration curve and Calib7.0.4 software (Stuiver and Reimer, 1993) applying a global marine reservoir correction of 400 years.~~A section from 116.25 cm to 124.75 cm in ODP-161-976A included three samples yielding the same AMS^{14}C age (see Table 1). Since there is no evidence for strong bioturbation, hiatuses or, turbidites we assume a rather continuous sedimentation rate throughout the core and, thus, decided to take the date at 120.25 cm as the only age control point for this depth interval since it has been dated twice on two different planktic foraminifera. The dates at 116.25 cm and 124.75 cm were not considered for the final age model in order to avoid artificially induced calculations of extraordinary high sedimentations rates in this thin sediment increment. The final age models have been calculated using Bacon (Blaauw and Christen, 2011). During age model processing all AMS^{14}C dates have been calibrated using the marine13 calibration curve including a global mean reservoir correction of 400 years (Reimer et al., 2013). Based on the AMS^{14}C dates, we assume a relatively high accumulation rate for ODP-161-976A. Accordingly, we set the mean accumulation parameter of the model to 50 yr/cm and run the model for 2.5 cm thick sections to allow for a certain variability of the accumulation rates throughout the section. The accumulation rate of GeoB5901-2 is expected to be lower in the analysed section based on AMS^{14}C data. Thus, the model parameters have been set to 100 yr/cm and 5 cm thick sections. In the case of sediment core ODP-161-976A the initial age model of Jiménez-Amat and Zahn (2015) ~~through the additional age control points~~was shifted significantly within the studied ~~time period was shifted massively. In this core,~~section by about 700 years. The reason for ~~the double-dated samples yielding slightly differing ^{14}C ages at the same sample depths (120.25 cm and 132.75 cm) the age with the lowest analytical error was chosen. Two additional~~ this shift are the new AMS^{14}C dates ~~(at 116.25 cm and 124.75 cm) have been oppositely excluded, because they resulted in the same age as the sample at 120.25 cm depth (Table 1). In order~~accomplished during this study emphasizing the need of a dense dating strategy. According to ~~achieve~~ the final age~~-depth models for both sediment cores, we linearly interpolated between the two closest AMS^{14}C age control points. Accordingly~~ model, sedimentation rates range between ~~10~~9.8 and ~~47~~50.0 cm/kyr in core ODP-161-976A and between 4.~~9~~8 and ~~68.6~~33.3 cm/kyr in core GeoB5901-2, respectively~~ and at~~. With 0.5 ~~sample~~cm sampling intervals ~~enabling thus~~ decadal to multi-decadal resolution is achieved. The studied section of sediment core ODP-161-976A dates between approximately 5.~~40~~4 to ~~2.92~~3.0 cal. ka BP exhibiting a temporal resolution between 10 to ~~60~~57 years per sample with continuous high resolution between 5.~~40~~4 and 4.~~62~~6 cal. ka BP. The analysed section of sediment core GeoB5901-2 dates between ~~3.07 ka BP~~approximately 6.2 and ~~5.33~~1.8 cal. ka BP resulting in a temporal resolution between ~~20~~15 and ~~95~~104 years per sample. Age models and sedimentation rates for both sediment cores are shown in Figure 2~~.~~ and 3, respectively.

2.3 Organic geochemical analysis and calculations

Lipids were extracted from the freeze-dried and finely ground sediment samples with an Accelerated Solvent Extractor (ASE-200, Dionex) at 100 bar and 100 °C using a 9:1 (v/v) mixture of dichloromethane (DCM) and methanol~~ (MeOH).~~. After extraction samples were de-sulphured by stirring for 30 minutes with activated copper. The de-sulphured lipids were subsequently separated by silica gel column chromatography using activated silica gel (450 °C for 4 h) into neutral (hexane) and polar (DCM) fractions containing n-alkanes and alkenones, respectively. The neutral fraction was further separated using silver-nitrate ($AgNO_3$) coated silica gel. Samples were then left at room temperature for approximately 24 hours for homogenisation.

Afterwards, n-alkanes were analysed by gas chromatography (GC) using an Agilent 6890N gas chromatograph equipped with a Restek XTI-5 capillary column (30 m x 320 µm x 0.25 µm) and a Flame Ionization Detector (FID) at ~~Christian-Albrechts University Kiel.~~the Institute of Geosciences, Kiel University. Example chromatograms are provided in the supplement of this paper. n-Alkanes were identified by comparison of their retention times with an external standard containing a series of n-alkane homologues of known concentration. On this basis, n-alkanes were also quantified using the FID peak areas calibrated against the external standard. For environmental interpretation the sum of terrestrial sourced, odd n-alkane homologues C_{27} to C_{33} is used. The mean analytical error (2σ) is 7.0 ng/ g sediment based on replicate analyses (n = 62).

Various studies used ratios among individual n-alkane homologues as environmental sensitive parameter, for example the Norm33 ratio (e.g. (Herrmann et al., 2016). The Norm33 ratio was calculated by the following equation:

$$\text{Norm33} = C_{33} / (C_{29} + C_{33}) \quad (1)$$

where C_X is the peak area of the n-alkane with x carbon atoms in the chromatogram. The mean analytical error (2σ) is 0.004 based on replicate analyses (n = 62).

Alkenones were analysed on a multi-dimensional, double gas column chromatography (MD-GC) set up with two Agilent 6890 gas chromatographs. The compounds ($C_{37:2}$ and $C_{37:3}$) were quantified by calibration to an external standard. The alkenone concentration is derived from the sum of the $C_{37:2}$ and $C_{37:3}$ isomers~~.~~ with a mean analytical error (2σ) of 6.9 ng/g sediment. The alkenone unsaturation index ($U^{K'}_{37}$) was obtained by using the peak areas of the aforementioned compounds applying the equation of Prahl and Wakeham (1987):

$$U^{K'}_{37} = C_{37:2} / (C_{37:2} + C_{37:3}) \quad (2)$$

where C_X represents the respective peak area in the chromatogram. The $U^{K'}_{37}$ index was subsequently transferred into annual mean SST using the calibration of Müller et al. (1998):

$$SST\ (°C) = (U_{37}^{K'} - 0.044) / 0.033 \quad (3)$$

The laboratory internal analytical error is approximately 0.12 °C, while the error of the calibration is 1.05 °C.

2.4 Planktic foraminiferal analysis and Modern Analogue Technique

For foraminiferal analysis sediment samples of approximately 10 cc were washed over 63 µm sieves, dried at 40 °C and, subsequently dry sieved. for larger fractions. Planktic foraminifera assemblages were analysed in the size fractions >150 µm enabling the application of commonly used transfer techniques for SST reconstructions based on relative abundances of 26 taxonomic categories within the assemblage, following conceptsconcept by Pflaumann et al. (1996). For reliable assemblage counts samples were dry split into aliquots of at least 300 specimens with a Kiel dry sample splitter. For SST estimates we used SIMMAX non-distance-weighted modern analogue technique, using a similarity index of >0.963 and based on 10 closest analogues (Pflaumann et al., 2003). A calibration data set was used combining 1066 core top assemblages from both, the North Atlantic as compiled by the MARGO projectBecause the study sites are influenced by Atlantic and Mediterranean ocean circulation, we combined an updated North Atlantic core top database (Hayes et al., 2005; Kucera et al., 2005a; Kucera et al., 2005b) and for the Mediterranean (Salgueiro et al., 2014). Modern temperature at 10 m water depth present-day SST was retrieved(Kucera et al., 2005a,b; Salgueiro et al., 2014) and the Mediterranean database (Hayes et al., 2005) with modern temperature at 10 m water depth taken from the World Ocean Atlas 1998 (Salgueiro et al., 2014). Seasonal temperatures are averaged for northern hemisphere summer (July to September) and for winter (December to February). This method as applied on core top samples yields an accuracy of better than 1 °C standard deviations for both, the Atlantic and the Mediterranean for summer and winter seasons (Hayes et al., 2005; Pflaumann et al., 2003; Salgueiro et al., 2014).Seasonal temperatures are averaged for northern hemisphere summer (July to September) and winter (December to February). This method applied on overall 1212 core top samples from the Atlantic and the Mediterranean yields an root-mean square error predicted accuracy of ± 1.3 °C for summer and winter seasons.

2.5 Proxy restrictions

Terrestrial n-alkanes derived from higher plant leaf waxes are commonly transported into the marine realm via aeolian and riverine transport (Bird et al., 1995; Conte and Weber, 2002; Schreuder et al., 2018) . The fraction of the riverine input in coastal areas is usually much higher compared to the aeolian input. Therefore, terrestrial n-alkane concentrations have already been successfully applied to study the riverine input in coastal settings in the Mediterranean (Abrantes et al., 2017; Cortina et al., 2016; Jalali et al., 2016; Jalali et al., 2017). More specifically, Rodrigo-Gámiz et al. (2015) have shown from radiogenic isotopes that in the Alboran Sea the riverine dominates the aeolian input during the studied time period. Consequently, the n-alkane concentrations analysed during this study are considered to primarily reflect the river discharge. The Norm33 ratio or the proportion of the C_{33} n-alkane homologue, respectively, is a function of a change in C4 plant distribution according to air temperature and/ or precipitation change (Bush and McInerney, 2013; Herrmann et al., 2016; Leider et al., 2013; Rommerskirchen et al., 2006; Vogts et al., 2009; Vogts et al., 2012). Because of the dominant riverine transport mechanism, it is assumed that both

proxies integrate spatially over the river catchment areas shown in Figure 1 and, thus, indicate climate conditions on a sub-regional level. The dominant main

3 Results

3.1 ODP-161-976A

Terrestrial proxies. The terrestrial n-alkane concentration varies between 67 and 714 ng/g sediment exhibiting no long-term trend across the covered time period from 5.4 to 3.0 cal. ka BP (Figure 3). Three distinct concentration minima below 200 ng/g sediment can be observed at 5.4 cal. ka BP, from 5.0 to 4.9 cal. ka BP and, from about 4.8 to 4.7 cal. ka BP. Less distinct minima are observed between 4.4 and 4.3 cal. ka BP and at about 3.7 cal. ka BP. A sharp increase towards high concentrations of up to 617 ng/g sediment is evident at about 4.2 cal. ka BP. n-Alkane concentrations appear to remain generally above 450 ng/g sediment until 3.8 cal. ka BP, when concentrations sharply decrease towards 209 ng/g sediment at 3.7 cal. ka BP. Afterwards, n-alkane concentrations reveal a slightly increasing trend towards 3.0 cal. ka BP. The Norm33 ratio exhibits no trends and varies between 0.29 and 0.49 (Figure 3). Four sharp increases towards values greater than 0.42 can be recognized at about 5.4 cal. ka BP, from 5.0 to 4.9 cal. ka BP, from 4.8 to 4.7 cal. ka BP and, at about 4.6 cal. ka BP. Apparently, the Norm33 maxima parallel the n-alkane concentration minima between 5.4 and 4.7 cal. ka BP.

Marine proxies. The alkenone derived annual mean SST remains quite stable between 18.9 °C and 20.0 °C (Figure 3). No trends are visible in the analysed time period. Only weak maxima in the annual mean SST of 0.5 to 1.0 °C in amplitude are apparent at about 5.4, 3.3 and, 3.0 cal. ka BP as well as between 5.1 and 4.6 cal. ka BP at about 100 year intervals (Figure 4). All foraminifera-derived seasonal SST reconstructions suggest similar stable temperature conditions without any obvious trends between 5.4 and 3.0 cal. ka BP. Summer SSTs vary around 22.8 ± 0.1 °C with several cooling episodes of up to 1 °C at about 5.0, 4.6, 4.3, 3.6, 3.3 and, 3.2 cal. ka BP. Winter SST generally vary around 15.0 ± 0.1 °C with weak warming episodes of up to 1 °C at about 5.0, 4.6, 4.3, 3.6, 3.3 and, 3.2 cal. ka BP. Thus, the winter SST maxima and summer SST minima are contemporaneous and result in a decreasing seasonal SST difference during these periods. Notably, the seasonal SST maxima or minima, respectively, do not parallel the SST maxima observed in the annual mean reconstruction. The alkenone concentration varies between about 224 and 440 ng/ g sediment and shows an increasing trend from 5.4 to 4.0 cal. ka BP followed by a decreasing trend towards 3.0 cal. ka BP (Figure 4). These trends are superimposed by several minima from 5.4 to 5.3 cal. ka BP, around 5.2, 5.0, 4.8 cal. ka BP, from 4.7 to 4.6 cal. ka BP, at 3.8 cal. ka BP and, from 3.1 to 3.0 cal. ka BP. The alkenone concentration is to some degree correlated (r = 0.61) to the annual mean SST across the studied time period (see supplement) with warmer annual mean SSTs paralleled by decreased alkenones content at about 5.4, 5.2, 4.9, 4.7, 4.6 cal. ka BP and, from 3.1 to 3.0 cal. ka BP (Figure 4).

3.2 GeoB5901-2

Terrestrial proxies. The terrestrial n-alkane concentration varies between 9 and 535 ng/g sediment and has an increasing trend towards younger ages between 5.4 and 3.0 cal. ka BP (Figure 3). During the studied time period at least three periods of decreasing n-alkane concentration below 100 ng/g sediment are found from 5.1 to 4.7 cal. ka BP, from 4.4 to 4.3 cal. ka BP and, at about 3.7 cal. ka BP. The oldest concentration minimum reveals a “W”-shaped pattern with increasing concentrations of up to 110 ng/g sediment at about 4.9 cal. ka BP. An additional concentration minimum (46 ng/g sediment) at 5.2 cal. ka BP is only corroborated by a single data point and, thus, not robust. The Norm33 varies without any trends between 0.31 and 0.51 showing high amplitude maxima with values above 0.42 at about 5.0, 4.8, 4.3 and, 3.7 cal. ka BP (Figure 3). Notably, the Norm33 reveals maxima during periods of low terrestrial n-alkane concentration.

Marine proxies. Alkenone derived annual mean SST vary without any trends between 5.5 and 3.0 cal. ka BP and reveal SSTs around 20.4 ± 0.3 °C with the exception of a period from about 4.3 to 3.9 cal. ka BP, where SST vary around 21.6 ± 0.6 °C with maximum SST being 22.7 °C (Figure 5). Foraminifera-derived summer SST reveal a slight decreasing trend towards the present between 6.2 and 1.8 cal. ka BP. Notably, between about 6.2 and 4.0 cal. ka BP the variability in summer SST is quite high with a mean of 22.4 ± 0.7 °C superimposed by several warm events of up to 23.9 °C that occur at 6.0, 5.8, 5.5, 4.7 and, 4.1 cal. ka BP. Also, the variability and the amplitudes of the warm events decrease towards the present. After 4.0 cal. ka BP summer SST vary around 21.7 ± 0.2 °C. Winter SST reveal a very similar pattern compared to the summer SST with high variability (16.0 ± 0.7 °C) until 4.0 cal. ka BP and less (16.8 ± 0.2 °C) afterwards. Overall, there is a warming trend from about 16 to 17 °C towards younger ages with major cooling episodes at 6.0, 5.8, 5.5, 4.7 and, 4.1 cal. ka BP. Winter SST decrease below 15.0 °C during most of these periods. The observed SST events in the seasonal reconstructions (summer and winter) are contemporaneous and result in an increasing seasonal difference of up to 9.3 °C during these events (Figure 5). Overall, the seasonal difference is decreasing towards younger ages from 6.4 to 4.7 °C. SST events within the seasonal reconstructions do not parallel any events in the alkenones derived annual mean SST. The warm period observed in the annual mean data between 4.3 and 3.9 cal. ka BP is not visible in the seasonal data. Also, the annual mean SST is very close to summer conditions, even exceeding those around 4.2 cal. ka BP.

3.3 Comparison of both sediment cores

In general, a good agreement between the n-alkane concentration in both sediment cores is apparent (Figure 3). This is corroborated by the high correlation coefficient (r = 0.82) for the period between 5.5 and 3.6 cal. ka BP. Since the correlation calculation is based on 100-year time slices (see supplement), there is not such a robust correlation in the younger part between 3.6 and 3.0 cal. ka BP (r = 0.04). Nonetheless, visual inspection implies a good agreement between both records when only the more pronounced minima and maxima are considered for this younger interval. The n-alkane concentration minima observed at about 4.3 and 3.7 cal. ka BP appear to be contemporaneous in both regions. Also, the two events from about 5.0 to 4.9 cal. ka BP and from 4.8 to 4.7 cal. ka BP in ODP-161-976A as well as the "W"-shaped event between 5.1 and 4.7 cal. ka BP in GeoB5901-2 correspond to a large extent. Only the drop towards low n-alkane concentrations between 5.1 and 5.0 cal. ka BP is offset by about 100 years (Figure 3). Bearing in the mind the chronological uncertainties around 5.0 cal. ka BP of ±110 years and ±160 years in the age model of GeoB5901-2 and ODP-161-976A, respectively, this offset likely is chronological bias. The Norm33 maxima of both sediment cores correspond well between 5.4 and 4.7 cal. ka BP (Figure 3).

With respect to absolute SST values and trends in the temperature reconstructions, differences between both cores are larger than for the terrestrial biomarker records. The alkenone-based as well as the foraminifera-derived winter SST were about 1 °C warmer in the Gulf of Cadiz, while summer SST were about 1°C warmer in the Alboran Sea. The most apparent difference between both regions is noticeable in the seasonal warm/cold events, which do not agree in their timing, as is the same for the much more moderate events observed in the alkenones-based SST records. Also, the overall trend in the difference in seasonal SST estimates is not similar in both regions. While in the Gulf of Cadiz (GeoB5901-2) the seasonal difference increases (i.e. summer warming and winter cooling), the seasonal difference in the Alboran Sea record (ODP-161-976A) record does not change significantly.

4 Discussion

4.1 Terrestrial climate conditions in southern Iberia

Terrestrial plants synthesize long chain n-alkanes in their leaves as coating for protection against water loss (Eglinton and Hamilton, 1967). These long chain n-alkanes are either eroded directly from the leaves by wind or deposited in the soils in autumn. Afterwards, n-alkanes are removed from the atmosphere or eroded from the soils by rain and are further transported into the marine realm via aeolian and riverine transport (e.g. Bird et al., 1995; Conte and Weber, 2002; Schreuder et al., 2018). The fraction of the riverine input in coastal areas is usually much higher compared to the aeolian input. Therefore, terrestrial n-alkane concentrations have already been successfully applied to study the riverine input in marine settings in the Mediterranean (Abrantes et al., 2017; Cortina et al., 2016; Jalali et al., 2016; 2017). More specifically, Rodrigo-Gámiz et al. (2015) have shown from radiogenic isotopes that in the Alboran Sea the riverine dominates the aeolian input during the studied time period. Because of the dominant riverine transport mechanism, it is assumed that both proxies integrate spatially over the river catchment areas shown in ~~catchment for sediment core GeoB5901-2 is the one of the Guadalquivir river draining into the Gulf of Cadiz. The smaller mountainous rivers draining the southern Sierra Nevada area are considered as more relevant for sediment core ODP-161-976A. A delivery of material from the Guadalquivir with the inflow of the Atlantic water through the Strait of Gibraltar might also be possible, though. Since the river discharge and also the plant growing season is strongly coupled to precipitation and the rainy season at the Iberian Peninsula is in winter, both proxies are probably biased towards the winter season (~~Figure 1 and, thus, indicate climate conditions for the entire southernmost Iberian Peninsula. The dominant catchment for sediment core GeoB5901-2 is the one of the Guadalquivir river draining into the Gulf of Cadiz. The smaller mountainous rivers draining the southern Sierra Nevada area are considered as more relevant for sediment core ODP-161-976A. A delivery of material from the Guadalquivir with the inflow of the Atlantic water through the Strait of Gibraltar ~~; Lionello, 2012).~~ cannot be excluded, though. Since the river discharge and also the plant growing season is strongly coupled to precipitation and the rainy season at the Iberian Peninsula is in winter (Figure 1; Lionello, 2012), the n-alkane proxies are probably biased towards the winter season. Consequently, intervals of very low n-alkane concentration in the studied cores are interpreted as periods of dry winters, which occurred in southern Iberia at 5.4 ± 0.3, from 5.1 to 4.9 ± 0.1, from 4.8 to 4.7 ± 0.1, from 4.4 to 4.3 ± 0.1 and, at 3.7 ± 0.1 cal. ka BP (Figure 3). Drier conditions at about 5.5 cal. ka BP

~~While the reconstructions from ODP-161-976A cover a period from 5.4 to 2.9 ka BP on high-resolution, the organic geochemical data from GeoB5901-2 covers a slightly shorter period from 5.3 to 3.0 ka BP also on generally lower resolution. The planktic foraminiferal data from GeoB5901-2 are shown for the period from 6.0 to 2.6 ka BP.~~

~~The terrestrial n-alkane concentration vary between 67 and 714 ng/g sediment in ODP-161-976A and between 9 and 535 ng/g sediment in GeoB5901-2 (Figure 3). While in ODP-161-976A n-alkane concentrations appear generally stable and no trends are recognizable, the data from GeoB5901-2 reveal an increasing trend towards younger ages. In the later core several distinct and brief changes towards concentrations below 100 ng/g sediment are observed from 5.1 to 4.7, from 4.4 to 4.3 and, from 3.8 to 3.7 ka BP. In ODP-161-976A minima of similar amplitude occur at 5.4, at 4.9, from 4.8 to 4.7, at ca. 4.6 as well as at 3.7 ka BP and, thus, are generally contemporaneous. High and overall stable concentrations above 500 ng/g sediment are observed between 4.3 and 3.8 ka BP in ODP-161-976A. The Norm33 of both sediment cores show no trends varying between 0.29 and 0.49 (Figure 3). Norm33 maxima in sediment core ODP-161-976A range from 5.4 to 5.3, from 5.0 to 4.9 and, from 3.0 to 2.9 ka BP. In addition, short-lived maxima occur at ca. 4.8, at ca. 4.6 and, at 4.2 ka BP. In GeoB5901-2 Norm33 maxima occur at 5.0, 4.7, 4.3 and, 3.7 ka BP.~~

The alkenone derived SST also exhibits relatively stable levels in both sediment cores with annual temperatures varying between 18.9 °C and 20.0 °C in ODP-161-976A and higher annual temperatures in GeoB5901-2 (20.0 °C to 22.7 °C; Figure 3). Notably, the ODP-161-976A record shows higher variability between 5.4 and 4.6 ka BP with maximal amplitudes of 1.0 °C varying around the mean of 19.4 °C. After 4.6 ka BP the mean annual SST slightly cools to very stable means of 19.1 °C. This stability is just interrupted by three short-lived maxima at 4.4, 3.7 and, 3.3 ka BP. From 3.0 ka BP annual SSTs increase again by about 0.5 °C. Annual mean SST in GeoB5901-2 vary stable around ca. 20.0 °C except for a pronounced warming of 2.1 °C at ca. 4.3 ka BP lasting until ca. 3.8 ka BP. The MAT-derived summer and winter SSTs also show stability in general with somewhat higher variations, though. ODP-161-976A summer SSTs show a stable mean of 22.6 °C with coolings of up to 1.0 °C at 4.9, 4.6, 4.3, 3.6 and, 3.1 ka BP. These coolings in summer are accompanied by warmings of similar amplitude in winter. In general, the winter SST varies around a mean of 15.2 °C, resulting in a stable seasonal SST difference of 7.4 °C in ODP-161-976A throughout the analysed period. During the seasonal SST maxima and minima, respectively, the seasonal difference decrease to minimal values of 5.7 °C. Compared with the winter and summer SSTs fluctuations the spring SSTs appear even more stable varying around 17.6 °C. While summer SST reconstructions of GeoB5901-2 indicate similar conditions around 22.1 °C, winter conditions are slightly warmer (16.4 °C). During summer warmings between 1-2 °C amplitude are observed at 6.0, from 5.9 to 5.6, from 5.5 to 5.4, at 4.7 and, at 4.1 ka BP. The summer warmings are accompanied by coolings of similar amplitude during winter. The seasonality slightly decreases towards younger ages from SST differences of 6.4 °C to 4.7 °C. During the summer warmings and winter coolings, respectively, the seasonal difference increases up to 9.3 °C.

The alkenone concentration in ODP-161-976A shows also stable conditions varying between 223 and 440 ng/g sediment with minima around 5.4, 5.2, 4.9, 4.7, 4.7 and, 3.0 ka BP. Maxima occur from 4.1 to 3.9 ka BP as well as around 3.7 ka BP (Figure 6).

Altogether, the data of both sediment cores allow the detailed comparison of seasonal climate variability in the terrestrial and marine realm during the mid- to late- Holocene in southern Iberia.

4.1 Terrestrial and marine environmental conditions in southern Iberia

The terrestrial n-alkane concentration record of GeoB5901-2 from the Gulf of Cadiz generally well matches the high resolution data of ODP-161-976A from the Alboran Sea (Figure 3). A notable difference appears at around 5.0 ka BP, when the GeoB5901-2 data records low concentrations since 5.1 ka BP, while low concentrations in ODP-161-976A appear not until 4.9 ka BP. This might be the result of dating uncertainties and/or due to the different river catchments with the ODP-161-976A data reflecting more the coastal Mediterranean climate, while the GeoB5901-2 data indicates more the climate variability of the hinterland and the northern Sierra Nevada. Apart from that time lag the amplitude of changes towards lower concentrations are remarkably similar, suggesting that both archives jointly robustly record the wider regional climatic conditions of the southern Iberian Peninsula.

Since the concentration of terrestrial n-alkanes in marine sediment cores strongly depend on the amount of river discharge, we interpret the periods of very low concentrations in the studied sediment cores as dry periods. Accordingly, drought episodes occurred in southern Iberia at 5.4, from ca. 5.1 to 4.9, from 4.8 to 4.7, at around 4.6, from 4.4 to 4.3 and, from 3.8 to 3.7 ka BP. All of these droughts are already well documented within dating uncertainties in various records from the area (Figure 4). A widespread trend towards drier conditions since ca. 5.5 ka BP is not only described from pollen sequences in southern Iberia (Fletcher and Sánchez Goñi, 2008; Jalut et al., 2009) but is also well in phase with the end of the African Humid Period (deMenocal et al., 2000). This transition appears to be marked by an aridity event~~ at ca. 5.5 ka BP~~ as evidenced by speleothem data from El Refugio Cave and Grotte de Piste (Walczak et al., 2015; Wassenburg et al., 2016) and high charcoal concentration in Cabo de Gata between ~~ca.~~about 5.4 and 5.3 cal. ka BP~~, respectively~~. Also, a contemporaneous remarkable decrease in Mediterranean forest was noticed by Ramos-Román et al. (2018b) from 5.5 to 5.4 cal. ka BP. Schröder et al. (2018) describe a drought event centred at ~~ca.~~about 5.3 cal. ka BP in Lake Medina (SW Iberia). The ~~drought events~~dry phases between ~~ca.~~about 5.1 and 4.9~~,~~ and from 4.8 to 4.7 ~~and, at ca. 4.6~~cal. ka BP observed in this study are corroborated by ~~several~~ regional speleothem records (Moreno et al., 2017; ~~Walczak et al., 2015;~~ Wassenburg et al., 2016)~~ as well as a charcoal record from Cabo de Gata (Burjachs and Expósito, 2015). A dramatic forest decline occurred between 5.0 and 4.5~~. A dramatic forest decline occurred between 5.0 and 4.5 cal. ka BP in SE Iberia (Pantaléon-Cano et al., 2003)~~.~~ along with high charcoal concentrations at Cabo de Gata indicating more frequent wild fires (Burjachs and Expósito, 2015). Moderate forest declines are found in pollen records from the Alboran Sea and Elx sequence ~~(~~(Figure 6; Burjachs and Expósito, 2015; Fletcher and Sánchez Goñi, 2008)~~. The drought event from 4.4 to 4.3 ka BP broadly coincides with the 4.2 ka event observed speleothem records from the Eastern and Central Mediterranean (Cheng et al., 2015; Zanchetta et al., 2016). According to Burjachs and Expósito (2015) the forest decline at Elx starts at ca. 4.3 ka BP and, thus, within dating accuracy may be considered as synchronous. Moreover, a forest decline these authors observe at Cabo de Gata centres around 4.4 ka BP. Ramos-Román et al. (2018a) observe aridity pulses at 4.5 and 4.3 ka BP in Padul peat record from the Sierra Nevada. Additional indications for a severe drought at that time~~. The following period between 4.4 and 3.8 cal. ka BP comprising the 4.2 ka event is discussed in more detail in chapter 4.2. The youngest dry phase found in this study at about 3.7 cal. ka BP has also been inferred from pollen data at~~come from lithological analyses in SE Iberia (Navarro-Hervás et al., 2014), a hiatus in pollen data from SW Iberia (Schröder et al., 2018) and, speleothem data (Moreno et al., 2017; Walczak et al., 2015; Wassenburg et al., 2016). The latest drought found in this study between 3.75 and 3.73 ka BP, although just lasting ca. 20 years, is described in pollen data from~~ Elx and Villaverde (Burjachs and Expósito, 2015; Carrión et al., 2016), while pollen data from the Alboran Sea indicate a moderate forest decline (Fletcher and Sánchez Goñi, 2008). ~~Additionally, indications~~Additional evidence for a severe dry ~~event~~phase around 3.7 cal. ka BP again ~~come~~stems from speleothem data (Moreno et al., 2017; Walczak et al., 2015).

Notably, in ~~our records~~ the GeoB5901-2 data all ~~observed drought~~dry episodes are paralleled by Norm33 maxima, while in the ODP-161-976A record the dry phases at about 5.4, 4.9 and, 4.7 cal. ka BP coincide with Norm33 maxima (~~Figure 4). These maxima~~Figure 3). A tendency towards higher n-alkane chain lengths, as revealed by increasing Norm33 values, is an indication for warmer and/or drier environmental conditions (Bush and McInerney, 2013; Leider et al., 2013; Rommerskirchen et al., 2006). A local study from southern Iberia further shows that increasing chain lengths are a function of decreasing water availability (García-Alix et al., 2017). Consequently, the Norm33 maxima observed in this study indicate ~~a shift towards a higher abundance of C4~~ high water stress for the plants~~, which are much more adapted~~ in relation to ~~drier (and warmer) conditions (e.g. Bush and McInerney, 2013). Moreover, our data gains support from~~the dry climate episodes. This is supported by Sierra Nevada bog sediments Borreguil de la Virgen and Borreguil de la Caldera (~~Figure 4~~Figure 6; García-Alix et al., 2018), which also ~~indicate an increase in C4 plant abundance~~show Norm33 maxima during ~~the droughts. In addition, pollen data from Elx and Padul record an increase in C4 grasses (*Poaceae*) at ca. 5.4, 5.0, 4.8, 4.4 and, 3.7 ka BP (Burjachs pers. comm., 2018; Ramos-Román et al., 2018b).~~such dry episodes. It has further been shown that Mediterranean forests declined while scrubs expanded in southern Iberia during the respective dry phases (Fletcher et al., 2007; Ramos-Román et al., 2018a;b). Accordingly, the ~~droughts~~dry episodes caused a ~~dramatic~~ noticeable response in the vegetation~~ shift although they occurred relatively fast within decades or even within~~

years., which suffered from decreasing water availability. This further implies that the vegetation in southern Iberia at that time was very sensitive to (winter) precipitation changes.

4.2 The 4.2 ka BP event

The manifestation of the 4.2 ka event across the Mediterranean is currently intensively debated with a particular focus on the western part. In the Eastern and Central Mediterranean many studies suggest a dry phase in the time window between 4.4 and 3.8 cal. ka BP (e.g. Calò et al., 2012; Cheng et al., 2015; Finné et al., 2017; Zanchetta et al., 2016). In the Western Mediterranean evidence for a dry phase associated with the 4.2 ka event comes from northern Algeria (Ruan et al., 2016) and pollen data from southern Iberia (Ramos-Román et al., 2018a). Furthermore, a drastic forest opening in SE Iberia is indicated from pollen sequences at Cabo de Gata around 4.4 cal. ka BP and at Elx at about 4.3 cal. ka BP (Figure 6; Burjachs and Expósito, 2015). Additional indications for a dry phase coinciding with the 4.2 ka event come from lithological analyses in SE Iberia (Navarro-Hervás et al., 2014), a hiatus in pollen data from SW Iberia (Schröder et al., 2018) and, speleothem data (Moreno et al., 2017; Walczak et al., 2015; Wassenburg et al., 2016). In contrast to the terrestrial variability our marine reconstructions suggest fairly stable conditions between 5.4 and 2.9 ka BP in the Alboran Sea and the Gulf of Cadiz (Figure 3). Alkenone derived annual mean SSTs from sediment core ODP-161-976A suggest temperatures around 19.2 °C, which are just slightly exceeding the modern annual SST of 18.0 °C (Locarnini et al., 2013). An overall cooling trend over the course of the Holocene in response to decreasing insolation is known on regional as well as on global scale (e.g. Cacho et al., 2001; NGRIP-Members, 2004), thus corroborating slightly warmer SSTs during the mid- and late-Holocene. Moreover, annual mean SSTs around 19 °C at that time are also found by other studies from the Alboran Sea (Cacho et al., 2001; Martrat et al., 2014; Pérez-Folgado et al., 2003; Rodrigo-Gámiz et al., 2014). Our seasonal reconstructions vary around 15.2 °C in winter and 22.6 °C in summer. While the winter temperatures a very close to the modern conditions (15.4 °C), summer SSTs indicate again slightly warmer conditions compared to recent SSTs (21.4 °C; Locarnini et al., 2013). Winter SSTs around 14.5 °C corroborating our results are also found by Pérez-Folgado et al. (2003), while they found warmer SSTs by about 2 °C during summer. On the other hand, our summer SST reconstructions confirm recent reconstructions from Rodrigo-Gámiz et al. (2014), who based on the long-chain diol index found summer SSTs around 22 °C. Some more subtle cooling events with SST declines of up to 1 °C occurred at 4.9, 4.6, 4.3, 3.6 and, 3.1 ka BP during summer and are accompanied by warming events of similar magnitude during winter. Consequently, seasonality diminished during these periods. Unfortunately, the low temporal resolution of available reference cores from the area hampers the correlation of such brief SST events. Detailed comparison between our SST data and the MPP data reveals a correlation between warmer annual mean SSTs and decreased MPP at around 5.4, 5.2, 4.9, 4.7, 4.6, 4.4, 3.7 and, 3.0 ka BP (Figure 6). Comparison with the SSTs events observed in the seasonal reconstructions is difficult due to the lower temporal resolution. Nonetheless, it appears that also spring SST increases during the MPP minima. Notably, the warming event from ca. 3.3 to 3.1 ka BP is not well reflected in the MPP data. Moreover, maximum MPP between 4.11 and 3.88 ka BP can be related with stable and relatively low annual and spring SSTs.

In the Gulf of Cadiz annual mean SSTs vary between 20.0 to 22.7 °C and are much warmer compared to recent temperatures (18.7 °C; Locarnini et al., 2013). Previous analyses of Kim et al. (2004) on the same sediment core yielded mean annual SSTs between 19 and 20 °C using a different SST calibration of Prahl et al. (1988), which would result in slightly cooler SSTs for our data as well. Annual mean SSTs around 20 °C in Gulf of Cadiz were also found by Cacho et al. (2001). The here reconstructed annual mean SSTs appear actually more close to summer conditions (Figure 3). From the foraminiferal analysis we reconstruct summer SSTs around 22.1 °C, which compare well with modern summer SSTs of 21.7 °C at the location (Locarnini et al., 2013). Supportingly, Salgueiro et al. (2014) found summer SSTs around ca. 23 °C in the Gulf of Cadiz. Also the reconstructed mean winter temperatures of 16.4 °C are in good agreement with the modern SSTs of 16.0 °C (Locarnini et al., 2013). During summer warming events of 1-2 °C amplitude are observed at 5.99, from 5.86 to 5.64, from 5.49 to 5.42, at 4.65 and, at 4.11 ka BP and these events are accompanied by cooling events during winter of similar amplitude. These events, notably, differ from the warm period found in the alkenone derived SST from 4.26 to 3.79 ka BP.

4.2 Possible

Compared to the prolonged dry phase between about 4.4 and 3.8 cal. ka BP recorded in speleothems from the Italian Peninsula and Algeria (Ruan et al., 2016; Zanchetta et al., 2016), our data indicate a more complex environmental pattern around the 4.2 ka event. The terrestrial n-alkane concentrations suggest a brief dry period from about 4.4 to 4.3 cal. ka BP followed by a rapid return to relatively moister conditions after about 4.2 cal. ka BP, which lasted until approximately 3.8 cal. ka BP. The Norm33 data, further, shows a peak in the GeoB5901-2 at about 4.3 cal. ka BP indicating that plants in the Guadalquivir basin were suffering from water stress. Contrastingly, the intermediate drop in n-alkane concentration in ODP-161-976A from the Alboran Sea is not paralleled by a Norm33 maximum. This might imply that the dry episode between about 4.4 and 4.3 cal. ka BP was more severely manifested in the lowlands of the Guadalquivir basin compared to the high-altitudes of the Sierra Nevada. Altogether, our reconstructions show that the onset of the dry phase at about 4.4 cal. ka BP is in line with proxy data from the Central Mediterranean, while the rapid return to relatively moister conditions at about 4.2 cal. ka lasting until about 3.8 cal. ka BP highlights regional differences in the duration of the 4.2 ka event compared to the prolonged dry phase associated with the 4.2 ka event in Italian and Algerian speleothems (Ruan et al., 2016; Zanchetta et al., 2016). This interpretation is corroborated by dry conditions at 4.4 cal. ka BP and wet conditions at 4.2 cal. ka BP found in ostracod shells from northern Morocco (Zielhofer et al., 2017; 2018).

4.3 Hydrological conditions in the Gulf of Cadiz and the Alboran Sea

In contrast to the terrestrial climate variability our marine reconstructions suggest fairly stable conditions between 5.4 and 3.0 cal. ka BP in the Alboran Sea and between 6.2 and 1.8 cal. ka BP the Gulf of Cadiz. The maximum range in the annual mean values based on alkenones is about 1 °C and, thus, within the calibration uncertainty. The low temporal resolution of previously studied cores from the area (below about 115 and 250 years for annual mean and seasonal data, respectively) further hampers the comparison with here observed SST events. Therefore, a careful interpretation of the alkenones-based SST results is required.

Alkenone derived SSTs from sediment core ODP-161-976A suggest annual mean temperatures between 18.9 and 20.0 °C (Figure 4), which exceed the modern values of about 18.0 °C (Locarnini et al., 2013). An overall cooling trend over the course of the mid- to late- Holocene in response to decreasing insolation (Figure 5) is known on regional as well as on global scale (e.g. Cacho et al., 2001; NGRIP-Members, 2004), thus corroborating warmer SSTs during the mid- Holocene compared to modern SSTs. Annual mean SST values around 19 °C at that time were also reconstructed by other studies from the Alboran Sea (Ausín et al., 2015; Cacho et al., 2001; Martrat et al., 2014; Pérez-Folgado et al., 2003; Rodrigo-Gámiz et al., 2014). Moreover, Cacho et al. (2001) described a cold SST event of about 1.5 °C in the Alboran Sea between 5.94 and 4.75 cal. ka BP. Our data from the Alboran Sea shows no cooling event of similar magnitude between 5.4 and 4.7 cal. ka BP. Bearing in mind the error of the calibration there might be a cooling at about 5.3 cal. ka BP in the order of just 0.5 °C, but surface water conditions between 5.4 and 4.7 cal. ka BP appear to have even been warmer compared to the period afterwards. In the Gulf of Cadiz alkenones-based SST values vary between 20.0 to 22.7

°C and are warmer compared to recent annual mean temperatures (18.7 °C; Locarnini et al., 2013). Higher SSTs during the mid-Holocene might be partly a consequence of higher insolation during this period. However, previous alkenone analyses of Kim et al. (2004) on the same sediment core yielded SST values between 19 and 20 °C using a different SST calibration of Prahl et al. (1988), which would result in slightly cooler SSTs for our data as well. Additionally, annual mean SSTs around 20 °C in Gulf of Cadiz were also found by Cacho et al. (2001).

Summer temperatures. Reconstructed summer SST based on foraminiferal assemblage variations vary around 22.8 °C in the Alboran Sea and around 22.4 and 21.7 °C before and after approximately 4.0 cal. ka BP, respectively, in the Gulf of Cadiz. Alboran Sea summer SSTs are exceeding modern ones (21.4 °C; Locarnini et al., 2013) likely due to higher insolation forcing during the mid- Holocene. This is even better demonstrated by the summer SST record in the Gulf of Cadiz. Here, summer SST estimates are progressively cooling towards mean summer SSTs around 21.7 °C, which perfectly agree with modern summer temperatures in the Gulf of Cadiz (21.7 °C; Locarnini et al., 2013). Reconstructed Alboran Sea summer SSTs are supported by Rodrigo-Gámiz et al. (2014), who estimated summer SSTs varying around 22 °C between 5.5 and 3.0 cal. ka BP. Pérez-Folgado et al. (2003) found even warmer summer SSTs between 24 and 25 °C in the Alboran Sea. This difference may be a result of the Pérez-Folgado et al. (2003) data calibrated against August temperatures only, while our method used the mean of the summer season (July – September). These authors also found a 0.5 °C cooling between about 5.0 and 4.5 cal. ka BP, when our data implies two cold events of approximately 1 °C at about 5.0 and 4.6 cal. ka BP. In the Gulf of Cadiz, in sediment core MD99-2339 (Salgueiro et al., 2014), summer SSTs vary between approximately 22 and 24 °C, exhibiting a cooling trend towards the present, which is in harmony with our summer SST reconstructions deduced from GeoB5901-2.

Winter temperatures. Winter SSTs in the Alboran Sea vary around ca. 15.0 °C between 5.4 and 3.0 cal. ka BP and agree with modern conditions (15.4 °C; Locarnini et al., 2013). Moreover, winter SSTs (February) around 14.5 °C during the mid- to late- Holocene reported by Pérez-Folgado et al. (2003) support our results. Winter SSTs between 16 and 17 °C between 6.2 and 1.8 cal. ka BP in the Gulf of Cadiz are also in good agreement with the modern winter SSTs of 16.0 °C (Locarnini et al., 2013). Slightly colder winter SSTs between 15 and 16 °C were reconstructed from dinocyst assemblages in the neighbouring core MD99-2339 (Penaud et al., 2016).

4.4 Potential drivers of terrestrial and marineoceanic climate variability

DuringUnder modern timesconditions the NAO is responsible for much of the variability in winter precipitation at the Iberian Peninsula (Hurrell, 1995; Zorita et al., 1992). Many paleo-climatic studies show thatprovide evidence for NAO-like climate variability was also evident duringsince the mid-Holocene (Abrantes et al., 2017; Deininger et al., 2017; Olsen et al., 2012). We here compare our drought events to a recently published North Atlantic storminess record from Filsø, Denmark (Figure 5; Goslin et al., 2018). Periods of increased storminess are indicating positive NAO-like conditions, which compare well with the drought events observed in this study. We, thus, compare the observed sequence of dry climate episodes to a reconstruction of NAO-like variability from Lake SS1220 in Greenland (Figure 4; Olsen et al., 2012). All dry phases observed in this study can be associated with positive excursions in the NAO reconstruction. Moreover, it is evident that a wetter period between about 4.2 and 3.8 cal. ka BP coincides with a period of more stable, less positive NAO-like conditions. Accordingly, we conclude that the droughtsdry phases observed between 5.4 and 2.93.0 cal. ka BP in southern Iberia are very likelywere caused by more dominant positive NAO-like conditions. It has to be cautioned, though, thatYet, other atmospheric circulation patterns like the Scandinavian and the East Atlantic pattern mightpatterns also contribute to the observedinfluence precipitation changesvariability at the Iberian Peninsula (Abrantes et al., 2017; Hernández et al., 2015). This may explain, why our records do not reveal dry episodes between 4.7 and 4.5 cal. ka BP and at about 3.1 cal. ka BP despite the NAO reconstruction suggests a strong positive circulation mode for these times. Interestingly, at around 5.2, 4.6 and, 3.0 cal. ka BP we found contemporaneous minima in the MPP and maxima in annual mean SSTs in the Alboran Sea (Figure 6). This linkage is also visible in the dry phases at about 5.4 cal. ka BP and between 5.0 and 4.8 cal. ka BP, while during those at about 4.3 and 3.7 cal. ka BP the warming of the annual mean SSTs was more pronounced. This linkage has previously been described by Ausín et al. (2015) since 7.7 cal. ka BP in the Alboran Sea and can also be related to NAO forcing. Currently, the inflow of the Atlantic Waters through the Strait of Gibraltar is strong under negative NAO conditions and, thereby, its flow within the Alboran Sea is shifted southwards. This promotes intensified upwelling of cold and nutrient rich waters, which also result in higher MPP (Sarhan et al., 2000). During positive NAO conditions, on the other hand, the inflow of the Atlantic Waters is weakened resulting in a more stable water column with limited upwelling and, thus, low MPP (Sarhan et al., 2000). Despite the calibration uncertainty of the annual mean SST reconstructions a similar mechanism is also indicated by our data during the mid- to late- Holocene. Accordingly, we conclude that a NAO-like variability was coupled to the terrestrial variability in southern Iberia as well as for the surface water variability in the Alboran Sea between 5.4 and 3.0 cal. ka BP.

It has alsofurther been suggested that NAO-like variability in the past iswas responsible for oceanic changes in the subtropical Atlantic such as the position of the Azores frontFront (Goslin et al., 2018; Repschläger et al., 2017) andas well as for increased upwelling as well asand related SST changes atalong the western Iberian margin (Abrantes et al., 2017). In more detail, Abrantes et al. (2017) suggest that warm winters and cool summers during the Medieval Climate Anomaly arewere related to positive NAO-like conditions at. For the western Iberian margin. During the mid- to late-Holocenetime interval between 6.2 and 1.8 cal. ka BP we cannot confirm a general link between the atmospheric and the oceanic conditions in the Gulf of Cadiz. While during the drought event between 4.4 and 4.3 ka BP our seasonal SSTs suggest no change, the alkenone-derived SST indicate a pronounced warming. On the other hand, during the drought event from 3.8 to 3.7 ka BP the Gulf of Cadiz experienced a sudden cooling in the annual mean SST, which lasted ca. 500 years. But in generalNAO and the hydrological conditions in the Gulf of Cadiz. Interestingly, we observe two notable differences between the oceanichydrological conditions in the Gulf of Cadiz and the Alboran Sea: (1) the summer/winter SST variability in the Gulf of Cadiz is opposite resulting in a greater seasonality, while seasonality decreases during summer/winter variability in the Alboran Sea and (2) the observed warming/ cooling events in both areas are not contemporaneous although the distance between both locations is less than 250 km. This suggests very different mechanisms driving the oceanic variability in the Gulf of Cadiz and the Alboran Sea. The SST variability in the Gulf of Cadiz compares well with the stacked Ice-Rafted Debris (IRD) data from Bond et al. (2001) (Figure 5) implying that the seasonal SST variability in the Gulf of Cadiz is driven by changes in the North Atlantic during Bond Events 3 and 4. Bond Event 2, on the other hand, is not visible in our SST data. Increased seasonality during mid-Holocene Bond Events so far is just described by Butruille et al. (2017) and van Nieuwenhove et al. (2018) for the Skagerrak and the northern North Atlantic, respectively. For the Subtropics our record from the Gulf of Cadiz is the first indicating increased seasonality from SST data associated with Bond Events. The Alboran Sea, instead, is not related to the SST development in the North Atlantic (i.e. Bond Events). But, the annual as well as seasonal SST development relate to the MPP, where higher annual mean temperatures are related to decreased productivity (Figure 6). Also, warmings during spring, which is the main blooming season of coccoliths in the Alboran Sea (Bosc et al., 2004), relate to MPP minima. These changes are most likely caused by dynamics of the Western Alboran Gyre. Ausín et al. (2015) also proposed a coupling of a stable water column (i.e. higher SST and decreased upwelling) and low productivity in the Alboran Sea with dry conditions in southern Iberia. Indeed, our data corroborates the presence of drier conditions during SST increases in the annual mean and spring temperatures and low productivity in the Alboran Sea. Following Ausín et al. (2015) these conditions are caused by positive NAO-like conditions slackening deep water formation in the Gulf of Lions and subsequently a weaker inflow of Atlantic Water through the Strait of Gibraltar. The good agreement of our drought events with the storminess data from Denmark (Goslin et al., 2018) underlines this interpretation. Consequently, NAO-like variability likely drives the oceanic variability in the Alboran Sea by altering the gyre circulation during seasonal SST events, while seasonality appears to decrease during summer/winter events in the Alboran Sea within methodological error and (2) the observed seasonal warming/ cooling events in both adjacent basins are not contemporaneous. This suggests different mechanisms driving the hydrological variability in the Gulf of Cadiz and the Alboran Sea. The pronounced seasonal SST variability in the Gulf of Cadiz is in general agreement with the stacked Ice-Rafted Debris (IRD) records for the North Atlantic (Bond et al., 2001; Figure 5). This implies that larger seasonal SST contrasts in the Gulf of Cadiz relate to periods of enhanced iceberg discharge in the North Atlantic during Bond Events 3 and 4. During Bond Events cold polar water masses have been advected as far south as the latitude of Britain (Bond et al., 1997). Our data suggests that this regime resulted in colder winter temperatures in the Gulf of Cadiz as well. Moreover, the Bond Events likely weakened the deep water formation in the North Atlantic by limiting the oceanic heat transport towards the north (Bond et al., 2001; Wanner et al., 2011). Repschläger et al. (2017) further proposed that early- Holocene freshwater forcing from the Laurentide ice sheet may have resulted in a weak subsurface heat transport from the Subtropical Gyre (STG) towards the North Atlantic and, subsequently, in a subsurface heat storage within the STG. Following these mechanisms, we hypothesize that during Bond Events 3 and 4 the northward heat transport was blocked due to freshwater forcing in the North Atlantic, which in turn results in a heat storage within the STG. During summer, when the Inter-Tropical Convergence Zone (ITCZ) moved northwards, these heated water masses probably reached the Gulf of Cadiz via the Azores Current resulting in warmer summer temperatures. These warmer water masses could also reach the Alboran Sea through the Strait of Gibraltar, but are not recorded within our data because summer temperatures in the Alboran Sea were generally warmer by about 1 °C during the studied period. Interestingly, it seems that annual mean SSTs in the Gulf of Cadiz warmed by up to 2 °C during Bond Event 3 (Figure 5). This might imply rather a growing season shift of the alkenones producing coccolithophores from spring to summer rather than a warming of the annual mean SSTs. Such a reaction of the coccolithophores might be also indicated to a lesser extent during Bond Event 2 when annual mean SSTs warmed by approximately 1 °C at about 3.2 cal. ka BP. Our data does not cover the whole interval, though. Also, Bond Event 4 is not entirely covered so that this interpretation remains hypothetical. But all in all, the influence of cold water from the North Atlantic during winter along with the influence of warmer subtropical water masses during summer likely resulted in a pronounced seasonality during Bond Events 3 and 4 (Figure 5). Notably, the amplitude of the seasonal events and their according high seasonality as well as the overall seasonality in the Gulf of Cadiz were decreasing towards the present. It is, moreover, interesting to note that Bond Event 2 is not visible in our seasonal SST records at all (Figure 5). The general decrease in seasonality in the Gulf of Cadiz can be attributed to decreasing summer insolation. We hypothesize that this is also true for the decreasing amplitude of the seasonal SST events. During Bond Event 4, when summer insolation was high, the more northward position of the ITCZ during summer allowed for a stronger inflow of warmer subtropical water masses into the Gulf of Cadiz. On the other hand, during winter the ITCZ was much further south compared to its present position, allowing enhanced southward flow of the colder water masses from the north. During Bond Event 3 the summer and winter positions of the ITCZ were already less extreme, thus, weakening the influence of either warm and cold water masses during summer or winter, respectively. Later, during Bond Event 2 seasonal movements of the ITCZ were even more limited that no influence of either cold water masses during winter or warm subtropical water masses during summer are recognizable by a pronounced seasonal temperature difference in the Gulf of Cadiz.

5 Conclusion

Our terrestrial proxies of both sediment cores agree well, revealing four drought events in southern Iberia from ca. 5.1 to 4.9, from 4.8 to 4.7, from 4.4 to 4.3 and, from 3.8 to 3.7 ka BP. The 4.2 ka event might be reflected in the drought occurring from 4.4 to 4.3 ka BP. Additional droughts are observed in the high-resolution core from the Alboran Sea at 5.4 and at 4.6 ka BP. All drought events occurred very fast within decades or even within years and are accompanied by a shift towards more C4 vegetation. The droughts observed in southern Iberia are closely correlating with NAO-like variability suggesting that the atmospheric circulation was an important driver of terrestrial variability in southern Iberia. Moreover, the oceanic variability observed in the Alboran Sea with higher annual and seasonal (winter and spring) SSTs and lower MPP seems to be driven by NAO-like variability as well. According to Ausín et al. (2015) positive NAO-like conditions alter the gyre circulation by limiting the Atlantic inflow through the Strait of Gibraltar, which results in a stable water column and decreased upwelling. This oceanic variability in the Alboran Sea is coinciding with droughts in southern Iberia. Contrastingly, oceanic variability in the Gulf of Cadiz shows no relation to the droughts or NAO-like variability, respectively. In fact, the Gulf of Cadiz reveals an opposite pattern compared to the Alboran Sea with summer warming and winter cooling. Also, the observed SST events in the Gulf of Cadiz and the Alboran Sea do not match temporarily implying different driving mechanisms. We found that the variability in the Gulf of Cadiz is related to Bond Events 3 and 4 in particular. Bond Event 2 is not resolved in our data. During Bond Events 3 and 4 we found a sharp increase in seasonality (i.e. summer warming and winter cooling) not described for this area before.

Consequently, we found that climate variability at the southern Iberian Peninsula during the mid- to late- Holocene strongly depends on North Atlantic forcing. While a North Atlantic atmospheric variability similar to modern day NAO is responsible for terrestrial as well as oceanic changes in the Alboran Sea, oceanic variability in the Gulf of Cadiz is more related to the marine forcing in the North Atlantic (i.e. Bond Events).

Two marine sediment cores from the Gulf of Cadiz and the Alboran Sea have been studied aiming at exploring the climatic variability with respect to precipitation and vegetation change in southern Iberia as well as resolving seasonal hydrological conditions during the mid- to late- Holocene. The following conclusions can be drawn from this study:

- Based on terrestrial n-alkane concentrations we found five major dry climate episodes in southern Iberia at 5.4 ± 0.3, from 5.1 to 4.9 ± 0.1, from 4.8 to 4.7 ± 0.1, from 4.4 to 4.3 ± 0.1 and, at 3.7 ± 0.1 cal. ka BP. These dry phases also impacted the vegetation, which suffered from environmental stress due to reduced water availability.
- The manifestation of the 4.2 ka event in southern Iberia appears to be shorter compared to the prolonged dry episode observed in other regions. Instead, our data suggests a distinct dry phase from 4.4 to 4.3 ± 0.1 cal. ka BP followed by a rapid shift towards wetter conditions at about 4.2 cal. ka BP, which lasted until approximately 3.8 cal. ka BP.

- SST reconstructions suggest fairly stable annual mean temperature conditions in the Alboran Sea and the Gulf of Cadiz with estimates values varying within the range of uncertainty of the calibration. Based on summer and winter SST estimates the new records imply different mechanisms driving the seasonal variability in these two oceanic basins. While in the Gulf of Cadiz opposite seasonal SST events (i.e. summer warming and winter cooling) of up to 2 °C amplitude enhanced the seasonal SST difference, only slight seasonal SST variations (i.e. summer cooling and winter warming) within the methodological uncertainty have been found in the Alboran Sea at different times.
- The new records further suggest that variability in precipitation and vegetation in southern Iberia and probably the hydrological variability in the Alboran Sea can be well explained by a NAO-like atmospheric circulation. Dominant positive NAO-like conditions appear contemporaneous with the observed dry phases over southern Iberia associated with slightly warmer annual mean SSTs and decreased MPP in the Alboran Sea.
- The variability of the seasonal SST contrasts in the Gulf of Cadiz seems to be closely related to North Atlantic Bond Events. We observe increasing seasonality with summer warming and winter cooling during Bond Events 3 and 4. We propose that during winter the southward transport of cold water masses from the North Atlantic affected the Gulf of Cadiz, while during summer warm water masses originating from the STG reached our study site. Bond Event 2 is not reflected by a larger difference in our seasonal SST reconstructions. This is likely due to decreasing summer insolation that also influences the seasonal movements of the subtropical Azores Front, which in the Gulf of Cadiz can also limit either the inflow of cold or warm water masses during winter and summer, respectively.

Data availability. The data reported in this paper are archived in Pangaea (www.pangaea.de).

Supplement. The supplement related to this article is available online at:

Author contribution. JS, the main author of this study (with contributions from all co-authors), performed the geochemical analyses ~~underlying the~~for reconstruction of precipitation, vegetation and, alkenones-based temperature ~~reconstructions~~. JS also established the new age models for the two sediment cores. Planktic foraminiferal analyses ~~underlying the~~ for seasonal SST ~~reconstructions~~estimates were provided by MW. ES ~~provided the~~ compiled the calibration data sets for the SIMMAX MAT analyses and computed SIMMAX SST. ~~TB and RS supported the processing of the biomarker in the lab at the Institute of Geosciences (CAU Kiel) with the~~TB was responsible for alkenone ~~evaluation~~analysis and quality control.

Competing interests. The authors declare that they have no conflict of interest.

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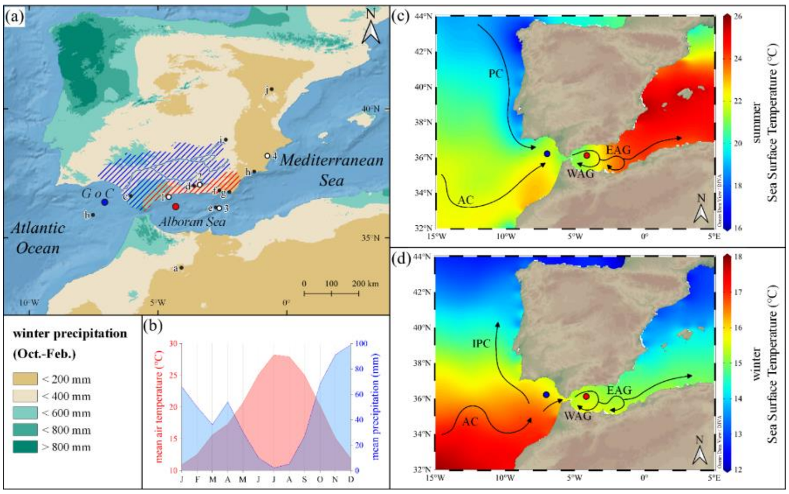
Figures and tables



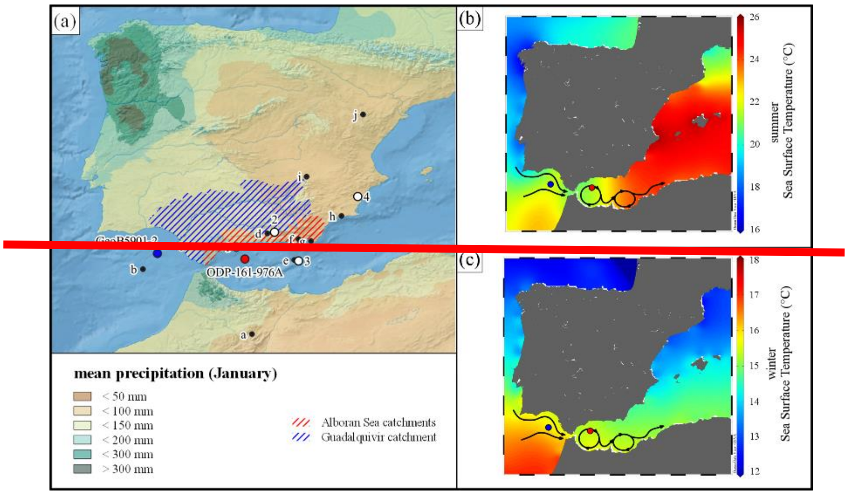


Figure 1: Overview maps. (a) overview with discussed (black dots) and shown (white dots) references at the Iberian Peninsula and studied sediment cores. Cores of this study: GeoB5901-2 (blue dot) and ODP-161-976A (red dot). Shown references: 1: El Refugio Cave (Walczak et al., 2015), 2: Borreguil de la Virgen and Borreguil de la Caldera (García-Alix et al., 2018), 3: MD95-2043 (Cacho et al., 2001; Fletcher and Sánchez Goñi, 2008; Martrat et al., 2014; Pérez-Folgado et al., 2003), 4: Elx (Burjachs and Expósito, 2015). Discussed references: a: Grotte de Piste (Wassenburg et al., 2016), b: MD99-2339 (Salgueiro et al., 2014), c: Lake Medina (Schröder et al., 2018), d: Padul (Ramos-Román et al., 2018a,b), e: TTR-293G (Rodrigo-Gámiz et al., 2014), f: San Rafael (Pantaléon-Cano et al., 2003), g: Cabo de Gata (Burjachs and Expósito, 2015), h: Mazarrón (Navarro-Hervás et al., 2014), i: Villaverde (Carrión et al., 2016) and, j: Ejulve cave (Moreno et al., 2017). The main river system and associated catchment of the Guadalquivir (hatched blue area) is shown as well as the river catchments of various small-scale rivers draining the southern Sierra Nevada area (hatched red area). The river catchments have been downloaded from the website of the European Environmental Agency. The colour shading indicates the mean winter precipitation ~~of January (~~(October to February) from 1970 ~~–~~to 2000~~) representative of the mean winter season precipitation~~ in the area. The data was provided by WorldClim V2 (Fick and Hijmans, 2017). ~~Mean summer (b) and winter (c~~(b) Annual average precipitation (blue) and air temperature (red) at Sevilla airport (1981-2010) show the high seasonality with rainy and cold winters and hot and dry summers. Data was provided by the Spanish State Meteorological Agency (AEMET). Mean summer (c) and winter (d) SSTs for the period 1955 – 2012 are shown. The data was provided by the World Ocean Atlas 2013 (Locarnini et al., 2013) and processed with Ocean Data View 5.1.2 (Schlitzer, 2018). Black arrows indicate the surface currents in the area including the gyres in the Alboran Sea. Blue and red dot mark locations of sediment cores GeoB5901-2 and ODP-161-976A, respectively. AC – Azores Current, IPC – Iberian Poleward Current, PC – Portugal Current, EAG – East Alboran Gyre, WAG – West Alboran Gyre.

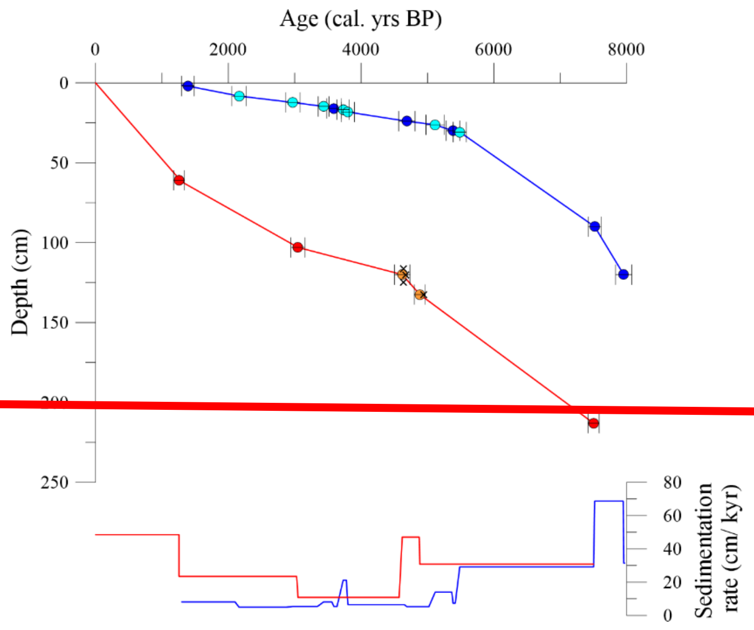
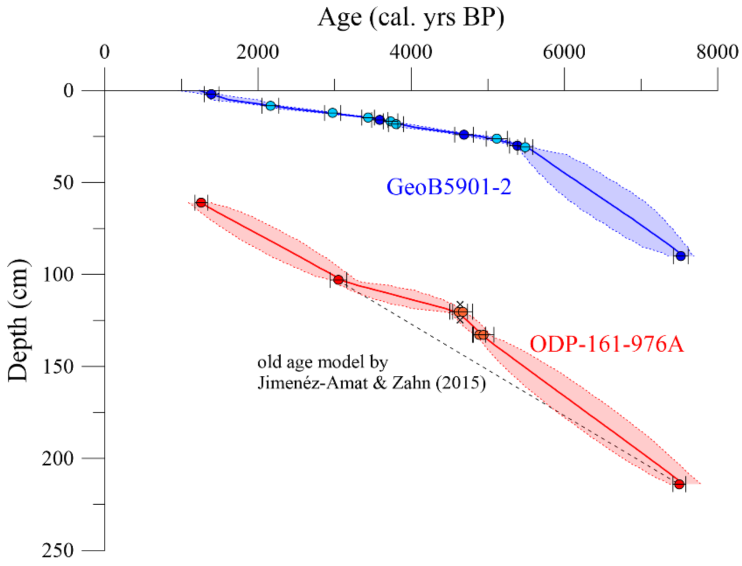


Figure 2: Age model. The age model from ODP-161-976A (red) is based on AMS^{14}C dates (red dots) from Combourieu Nebout et al. (2002)~~, which have been re-calibrated by the author and two new AMS^{14}C dates from this study (orange dots). Black crosses mark the four AMS^{14}C dates of sediment core ODP-161-976A, which are not considered. The Age model of GeoB5901-2 (blue) is based on AMS^{14}C datings done by Kim et al. (2004) re-calibrated by the author (dark blue dots) and seven new AMS^{14}C dates accomplished during this study (light blue) (for all AMS^{14}C datings see Table 1). On the bottom the according sedimentation rates of sediment cores ODP-161-976A (red) and GeoB5901-2 (blue) are shown.~~and new AMS^{14}C dates from this study (orange dots). Black crosses mark AMS^{14}C dates considered as outliers. Black dotted line indicates the shift of the previous age model from Jiménez-Amat and Zahn (2015). The Age model of GeoB5901-2 (blue) is based on AMS^{14}C datings done by Kim et al. (2004) (dark blue dots) and new AMS^{14}C dates accomplished during this study (light blue dots). The red and blue shaded area indicates the 95% probability of the age model for ODP-161-976A and GeoB5901-2, respectively. All AMS^{14}C dates are listed in Table 1.



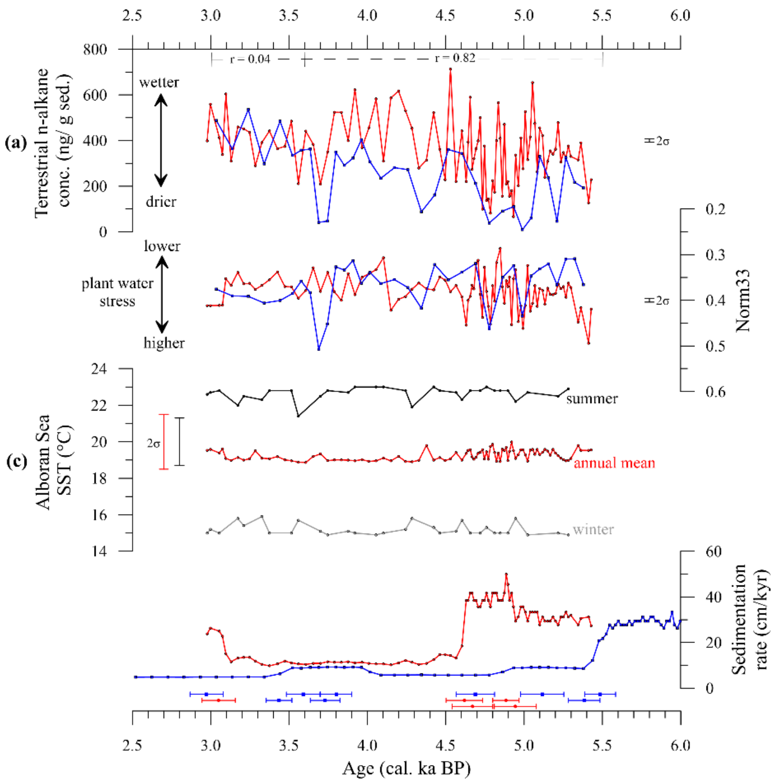
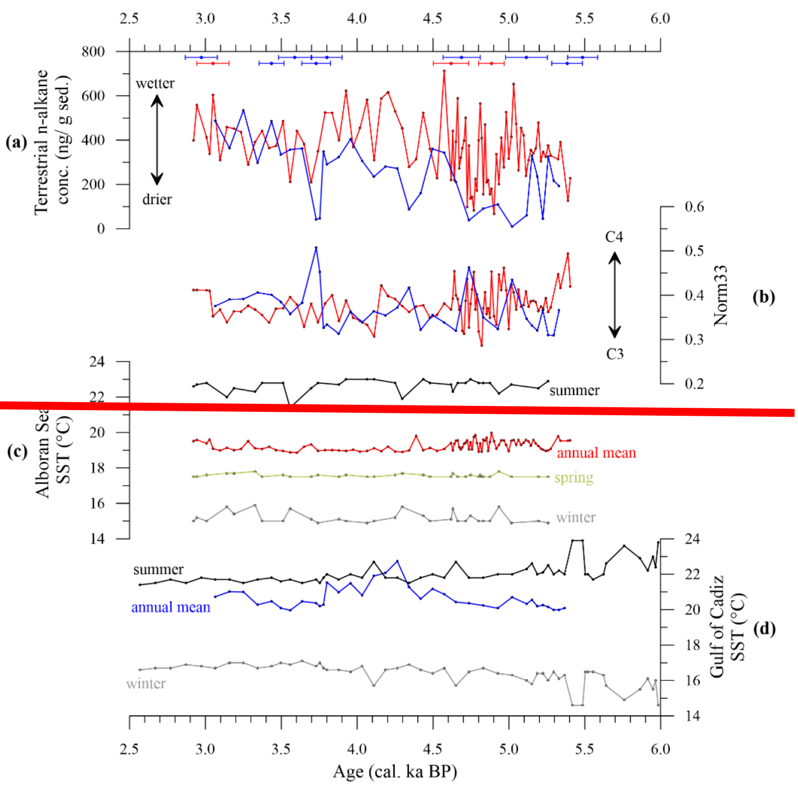
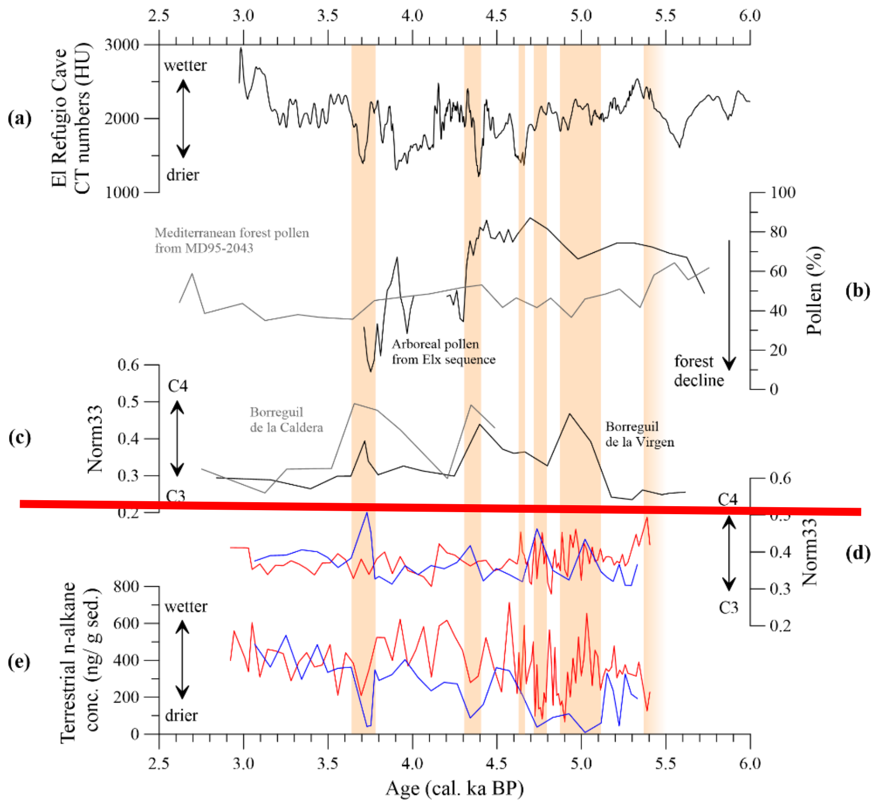


Figure 3: Data of marine sediment cores ODP-161-976A (red) and GeoB5901-2 (blue). (a) Terrestrial n-alkane concentration (ΣC_{27-33}) indicative of precipitation change. Pearson's correlation coefficient has been calculated based on 100-year time slices for two periods (see supplement for further information). (b) Norm33 n-alkane ratio showing ~~C3 vs. C4~~ plant ~~input~~water stress. (c) ~~alkenone~~Alkenone and planktic foraminifera based Sea Surface Temperature (SST) reconstruction from ODP-161-976A (black – summer; grey – winter; ~~green – spring;~~ red – annual mean). ~~(d) alkenone and planktic foraminifera based SST reconstruction from GeoB5901-2 (black – summer; grey – winter; blue –~~ Error bars indicate the uncertainty of the calibration for the annual mean~~)~~ (red) and seasonal (black) reconstructions. (d) Sedimentation rate of both cores are shown for comparison. Coloured dots at the ~~top~~bottom show AMS^{14}C age control points and associated 2σ errors.

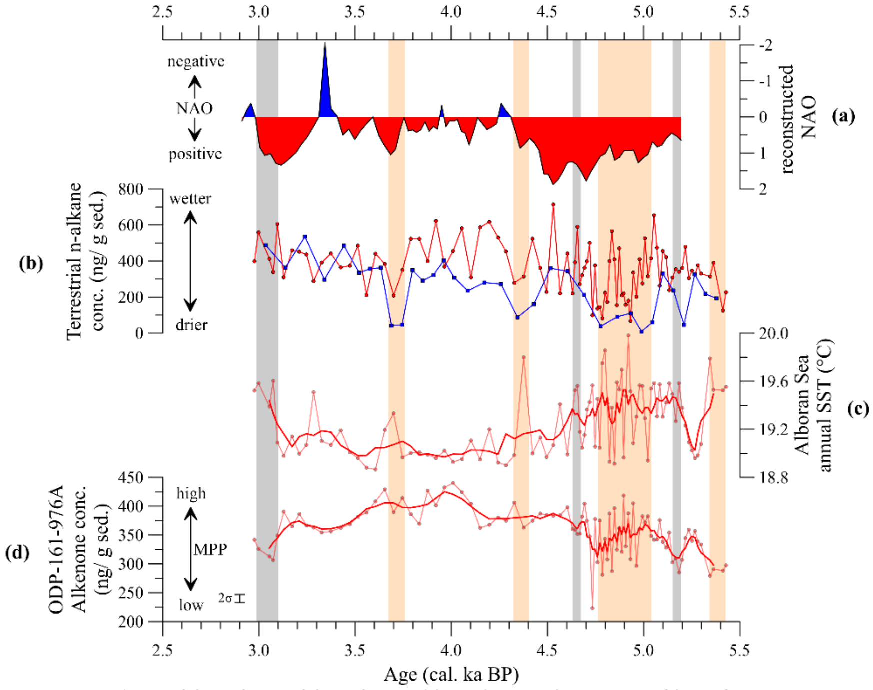


2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
(a)
Terrestrial n-alkane conc. (ng/ g sed.)
800 600 400 200 0
wetter
drier
(b)
Norm33
0.6 0.5 0.4 0.3 0.2
C4
C3
(c)
Alboran Sea SST (°C)
24 22 20 18 16 14
summer
annual mean
spring
winter
(d)
Gulf of Cadiz SST (°C)
24 22 20 18 16 14
summer
annual mean
winter
Age (cal. ka BP)



2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
(a)
El Refugio Cave CT numbers (HU)
3000 2000 1000
wetter
drier
(b)
Pollen (%)
100 80 60 40 20 0
Mediterranean forest pollen from MD95-2043
Arboreal pollen from Elx sequence
forest decline
(c)
Norm33
0.6 0.5 0.4 0.3 0.2
C4
C3
Borreguil de la Caldera
Borreguil de la Virgen
(d)
Norm33
0.6 0.4 0.3 0.2
C4
C3
(e)
Terrestrial n-alkane conc. (ng/ g sed.)
800 600 400 200 0
wetter
drier
Age (cal. ka BP)

Figure 4: Potential driver of atmospheric and Alboran Sea climate variability. (a) NAO reconstruction (Olsen et al., 2012). (b) Terrestrial n-alkane concentrations from ODP-161-976A (red) and GeoB5901-2 (blue) (this study). (c) Annual mean SST from ODP-161-976A (this study). (d) Alkenone concentration from ODP-161-976A indicative of MPP variability (this study). Thick red lines show the 5-point running means. Orange bars indicate dry phases observed in this study, while grey bars indicate periods of annual mean SST maxima and MPP minima at the core location of ODP-161-976A.



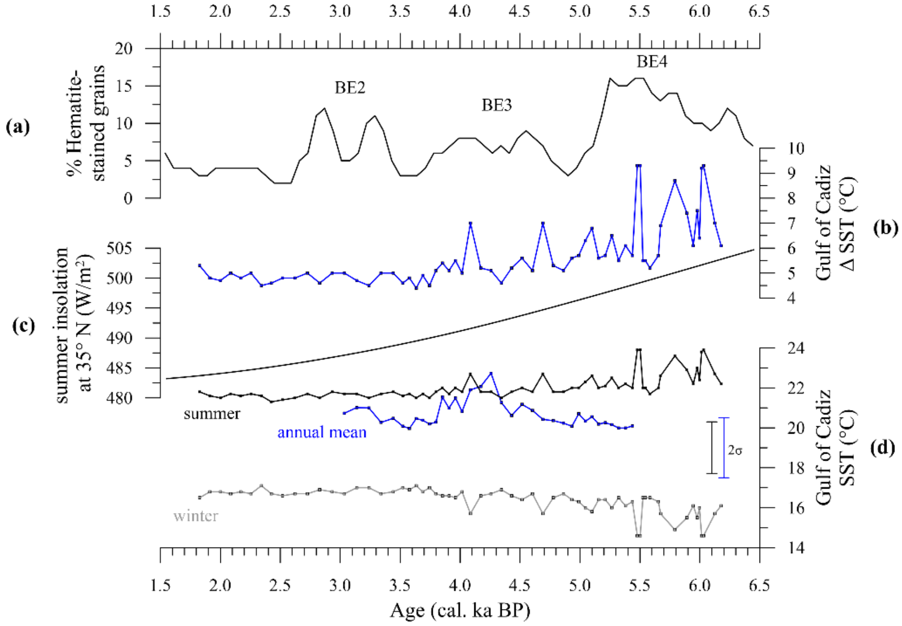
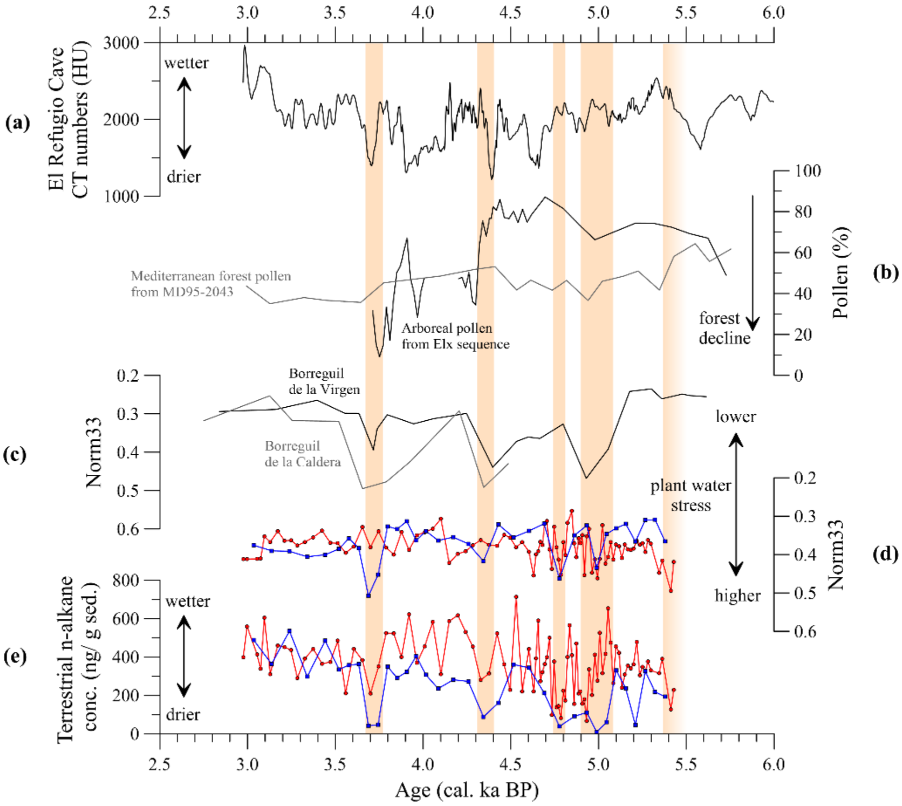
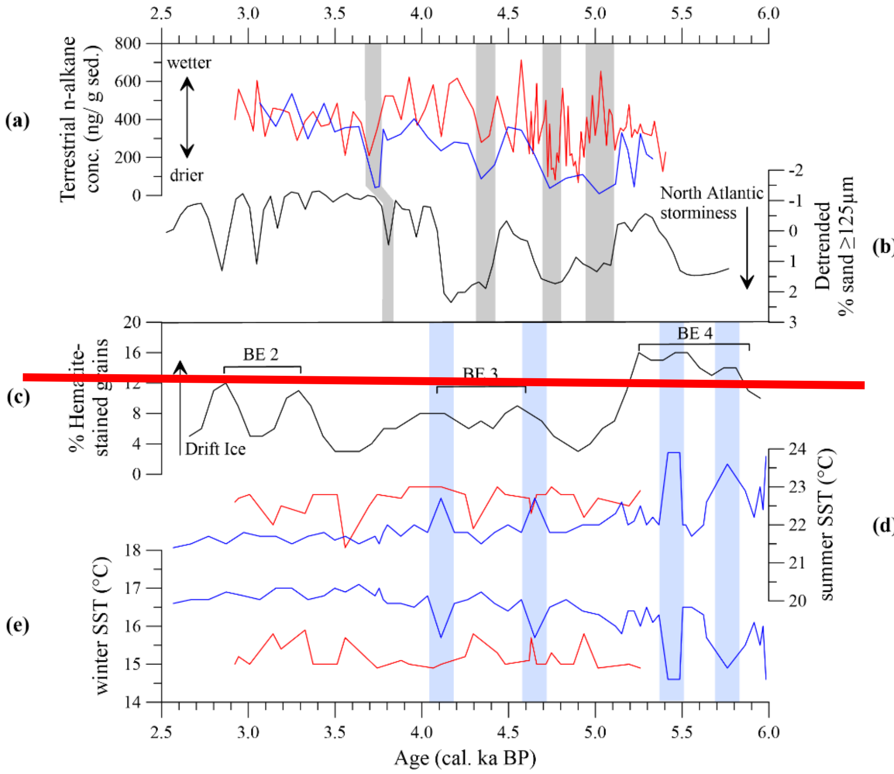


Figure 5: Oceanic variability in the Gulf of Cadiz. (a) Stacked hematite-stained grain percentages from marine sediment cores in the North Atlantic showing Bond Events (BEs) 2 to 4 (Bond et al., 2001). (b) Seasonal SST difference (winter – summer) deduced from the GeoB5901-2 foraminiferal data. (c) Summer insolation at 35° N (Laskar et al., 2004). (d) Alkenone and planktic foraminifera based SST reconstruction from GeoB5901-2 (black – summer; grey – winter; blue – annual mean). Error bars indicate the uncertainty of the calibration for the annual mean (blue) and seasonal (black) reconstructions.

Figure 6:~~:~~ Proxy data from the Iberian Peninsula. (a) ~~speleothem~~Speleothem density data from El Refugio Cave (Walczak et al., 2015). (b) ~~pollen~~Pollen data from Elx sequence (Burjachs and Expósito, 2015; Burjachs et al., 1997) and marine sediment core MD95-2043 (Fletcher and Sánchez Goñi, 2008). (c) Norm33 n-alkane ratios from Borreguil de la Caldera and Borreguil de la Virgen. These data have been calculated on the basis of n-alkane raw data from ~~(~~García-Alix et al~~., .~~ (2018). (d) Norm33 n-alkane ratios from ODP-161-976A (red) and GeoB5901-2 (blue) (this study~~)~~). (e) ~~terrestrial~~Terrestrial n-alkane ~~concentration~~concentrations from ODP-161-976A (red) and ~~Geob5901~~GeoB5901-2



(blue) (this study). The orange bars indicate dry ~~events recognized~~phases observed in this study. The locations of all the references are shown in Figure 1.



~~**Figure 5: Potential drivers of atmospheric (upper panel) and oceanic (lower panel) climate variability in the Atlantic realm. (a) terrestrial n-alkane concentration from ODP-161-976A (red) and Geob5901-2 (blue) (this study). (b) North Atlantic storminess data of sediment core F06 from Filsø (Denmark) indicative of NAO-like atmospheric variability (Goslin et al., 2018) (c) stacked hematite-stained grain data from the North Atlantic showing the Bond Events (BE) 2 to 4 (Bond et al., 2001) (d) summer and (e) winter SST from ODP-161-976A (red) and Geob5901-2 (blue) (this study). The grey bars indicate dry events and the blue bars major cooling events in the Gulf of Cadiz recognized in this study.**~~

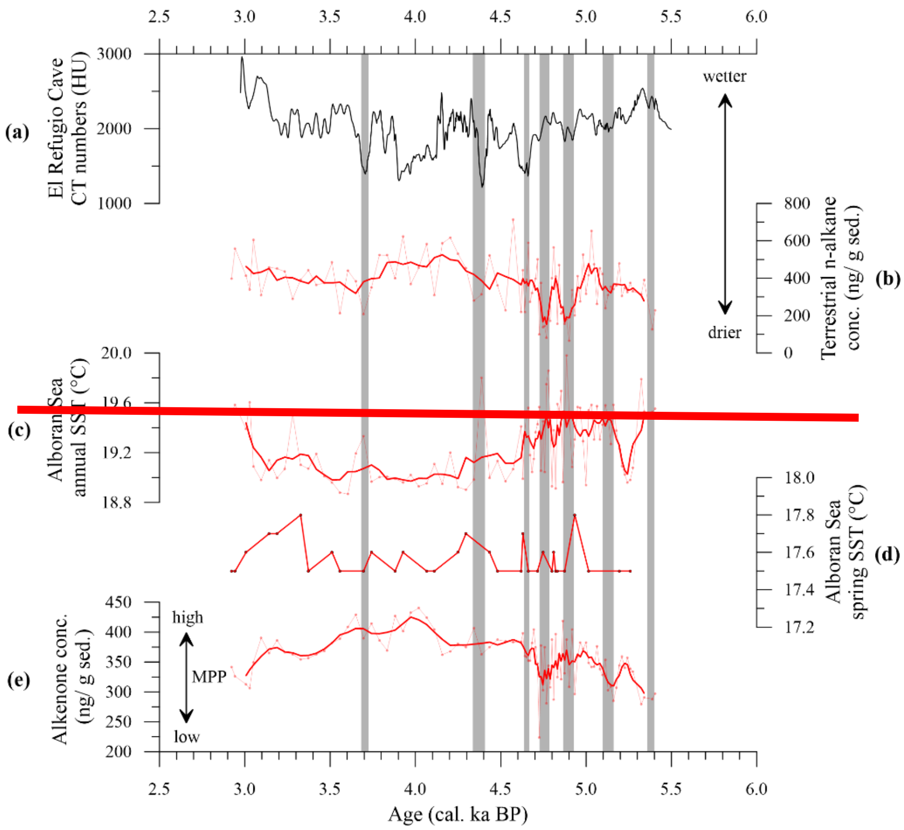


Figure 6: Atmospheric and oceanic variability in the Alboran Sea (ODP 161-976A). (a) speleothem density data from El Refugio Cave (Walczak et al., 2015) (b) terrestrial n-alkane concentration (c) annual mean SST deduced from alkenones (d) spring SST deduced from planktic foraminifera and (e) alkenone concentration indicative of the MPP. Thick red lines in (b), (c) and, (e) are 5-point-running means for better vizualisation, while the raw data is shown in light colors. Grey bars show periods of coupled atmospheric and oceanic variability (i.e. droughts, SST warming and, low MPP) in the Alboran Sea.

Table 1: Age model of sediment cores ODP-161-976 and GeoB5901-2. All dates from previous studies have been re-calibrated. Not considered dates are shown in grey.

Sediment core	Lab. No.	Depth (cm)	AMS^{14}C age (yr BP) ±~~-~~σ	~~Calibrated~~Cal. age (yr BP) ± 2σ	Dated material	Reference
GeoB5901-2	KIA-14522	2.00	1840 ± 35	1392 ± 96	planktic mix	~~(~~Kim et al~~.,~~. (2004)
GeoB5901-2	KIA-53006	8.25	2485 ± 25	2162 ± 110	*G. ruber* w~~+~~ +p	this study
GeoB5901-2	KIA-53005	12.25	3185 ± 27	2973 ± 106	*G. ruber* w~~+~~ +p	this study
GeoB5901-2	KIA-53002	14.75	3545 ± 26	3436 ± 82	*G. ruber* w~~+~~ +p	this study
GeoB5901-2	KIA-14521	16.00	3685 ± 35	3590 ± 108	planktic mix	~~(~~Kim et al~~.,~~. (2004)
GeoB5901-2	KIA-53003	16.75	3789 ± 27	3730 ± 95	*G. ruber* w~~+~~ +p	this study
GeoB5901-2	KIA-53004	18.25	3852 ± 27	3801 ± 100	*G. ruber* w~~+~~ +p	this study
GeoB5901-2	KIA-14520	24.00	4500 ± 40	4689 ± 123	planktic mix	~~(~~Kim et al~~.,~~. (2004)
GeoB5901-2	KIA-52665	26.25	4820 ± 35	5116 ± 138	*G. ruber* w~~+~~ +p	this study
GeoB5901-2	KIA-14518	30.00	5035 ± 40	5384 ± 101	planktic mix	~~(~~Kim et al~~.,~~. (2004)
GeoB5901-2	KIA-52666	30.75	5130 ± 40	5486 ± 99	*G. ruber* w~~+~~ +p	this study
GeoB5901-2	KIA-14516	90.00	7035 ± 55	7518 ± 97	planktic mix	~~(~~Kim et al~~.,~~. (2004)
GeoB5901-2	KIA-13704	120.00	7495 ± 50	7955 ± 121	planktic mix	~~(~~Kim et al~~.,~~. (2004)
ODP-161-976C	KIA-6435	61.00	1710 ± 40	1259 ± 82	*G. bulloides*	~~(~~Combourieu Nebout et al~~.,~~. (2002)
ODP-161-976C	KIA-6436	103.00	3235 ± 30	3050 ± 106	*G. bulloides*	~~(~~Combourieu Nebout et al~~.,~~. (2002)
ODP-161-976A	KIA-53326	116.25	4435 ± 35	4636 ± 138	*G. bulloides*	this study
ODP-161-976A	KIA-53235	120.25	4435 ± 30	4619 ± 117	*G. ruber* w~~+~~ +p	this study
ODP-161-976A	KIA-53327	120.25	4480 ± 40	4671 ± 130	*G. bulloides*	this study
ODP-161-976A	KIA-53236	124.75	4435 ± 35	4636 ± 138	*G. ruber* w~~+~~ +p	this study
ODP-161-976A	KIA-53234	132.75	4650 ± 35	4885 ± 84	*G. ruber* w~~+~~ +p	this study
ODP-161-976A	KIA-53325	132.75	4700 ± 50	4945 ± 134	*G. bulloides*	this study
ODP-161-976C	KIA-6437	~~213~~214.00	7010 ± 50	7500 ± 84	*G. bulloides*	~~(~~Combourieu Nebout et al~~.,~~. (2002)