Dear Raymond Bradley,

Anonymous Referee #1 gave as important suggestions about our proxy data set. We considered his comments in the fully revised version of the manuscript.

"Concern: 1) The authors have published the interpretation of the 18O record in Zielhofer et al. (2017). They interpret the 18O record as a proxy for winter precipitation, which is based on a multi-proxy approach with a charcoal, and cedar pollen abundance records. Although, I can follow their line of arguments that cedar trees need enough moisture and the charcoal record may represent fire activity, I don't see a clear correlation between the charcoal record and the cedar pollen abundance."

In the first version of the CP manuscript, we applied a multi-proxy interpretation that is based on two scales. Orbital scale and multi-centennial to millennial scale.

At orbital scale $\delta^{18}O$ values increase from approx. +3 to +5 ‰ in the Early Holocene to values from +5 to +7 ‰ in the Late Holocene. As the most straightforward scenario for a subhumid, closed basin (Roberts et al., 2008) this implies a decrease of the precipitation/evaporation ratio with generally more arid conditions towards the Late Holocene. This corresponds with Sidi Ali diatom, TOC and carbonate records that indicate in average higher lake levels during the Early Holocene and lower levels at later stages (Zielhofer et al., 2017).

These findings seem to contradict the *Cedrus* pollen record from Lake Sidi Ali (Campbell et al., 2017) that shows a low or even missing occurrence of cedars during the Early Holocene, indicating reduced moisture availability at that time. However, reduced moisture availability for the cool-preferring cedar seems to be the result of enhanced summer heat during the Early Holocene. Due to their shallow roots, cedars are vulnerable to summer heat in contrast to the warm tolerant and deep-rooting evergreen oaks that dominate the Sidi Ali pollen record during the Early Holocene (Campbell et al., 2017). In this context, we attest summer temperature-driven drought stress and not winter precipitation as the limiting factor for the long-term trend of Holocene cedar occurrence in the Middle Atlas. This inference is in good agreement with the orbital-forced summer insolation maximum during the Early Holocene (Berger 1978) and the chironomid-based summer temperature reconstructions that indicate enhanced Mediterranean summer temperatures during the Early Holocene as well (Samartin et al., 2017).

Following our interpretation, at orbital scale our proxies show reduced winter precipitation (high $\delta^{18}O$) and (summer) cool conditions (high amount of *Cedrus* pollen) during the Late Holocene and enhanced winter precipitation (low $\delta^{18}O$) and enhanced summer heat (low *Cedrus* pollen amounts) during the Early Holocene. We think that this is currently the best interpretation but alternatives may exist. Furthermore, we worked out that enhanced $\delta^{18}O$ values might be also the result of a specific origin and seasonality of the precipitation-bearing air masses. We assume that Late Holocene precipitation from springtime Mediterranean cyclones reveal higher $\delta^{18}O$ values than Atlantic winter rains (Zielhofer et al. 2017).

However, we have to agree with Referee #1 that the orbital pattern between *Cedrus* and Sidi Ali $\delta^{18}O$ is not clearly visible in the comparison of the *Cedrus* record with our $\delta^{18}O$ record at multi-centennial and millennial time scales. In the fully revised manuscript, we discuss this issue and argue that the *Cedrus* record is influenced by summer heat stress and that summer heat might be predominantly forced by the subtropical high and not by North Atlantic air masses. This is visible in the "in phase" pattern between subtropical summer SST and our *Cedrus* record (new Figure 2). We argue that reduced summer heat ("cooling at Sidi Ali") can be in phase with reduced winter rainfall at Sidi Ali (e.g. 8.2 and 10.2 ka) but that there are also indications for out-of-phase pattern (e.g. during the Late Holocene and also at 7.3 and 9.3 cal ka BP). Hence, this out-of-phase pattern might be influenced by different forcing mechanisms for summer cooling (sub-tropical high) and winter rain (North Atlantic winter cyclones). In the fully revised manuscript, we follow this line of argument that might explain the weak matching between *Cedrus* and δ^{18}O at multi-centennial to millennial time scales. In the fully revised manuscript, we argue that the Sidi Ali δ^{18}O record is "in phase" with Bond's HSG record to support the idea of a teleconnection between Western Mediterranean winter precipitation and North Atlantic cooling. As *Cedrus* might reflect predominantly summer cooling we are not be able to detect North Atlantic (winter) cooling from our own record directly.

Due to uncertainties in age models (Sidi Ali vs. Bond record), we are not able to provide significant correlations between HSG and Sidi Ali δ^{18}O. Here, we argument more carefully now as suggested by referee #1. We avoid the term "correlation" and use the terms "in phase pattern" and "out of phase". Further, we apply lowpass filters (programme PAST) that reduce the centennial-scale variabilities of the proxy records (see new Figs. 2 and 3). In the fully revised manuscript, therefore, we argue more carefully. The blue and orange bars in Figure 3 indicate in phase pattern of the filtered HSG and δ^{18}O records.

Further, we agree with referee #1 that the charcoal record is a difficult proxy for the interpretation of landscape dynamics at multi-centennial time scales. There might be no consistent matching between the charcoal and vegetation record. The charcoal can be dominated by individual fire events and these do not appear systematically linked to the fluctuations in the Cedrus pollen abundance. The charcoal is a complex proxy – influenced by climate but also by fuel availability, and the relative importance of these two factors seems to shift over the Holocene (Campbell et al. 2017). Therefore, we will not use the charcoal record in the revised manuscript.

2) The authors clearly state that lake Sidi Ali is a closed basin lake where the Precipitation-Evaporation balance (P-E) plays an essential role in controlling the oxygen isotope composition. This is evident from the highly elevated present day 18O values of the water that range from 0 to +4 ‰ whereas the surrounding karst springs and streams range from -6 to -9 ‰ (Zielhofer et al., 2017). The lake shows a huge range in surface area varying from 2 to 2.8 km2 (Zielhofer et al., 2017) due to varying P-E balance on interannual/decadal timescales. This is extremely likely visible in the 18O of the water. This can be controlled by both evaporation during the dry season, and by replenishment during the winter season, but not only through winter precipitation.

We fully agree with Referee #1 that the lake is strongly affected by evaporation. This was clearly stated in the first version of the manuscript and is again stated in the fully revised version (page 8 line 5). Nevertheless, we tried to work out in our published manuscripts (Zielhofer et al. 2017 and Campbell et al. 2017) that the δ^{18}O record at Sidi Ali is a complex proxy and that the most convincing line of argument results in the variability of winter rains.

3) In order to show that the ostracod 18O variability represents the 18O of the water the authors calculate the theoretical calcite 18O values based on the present-day water 18O and the isotope fractionation factor from Friedman and O'Neill (1977). Why not using the much more recent isotope fractionation factor from Kim and O'Neill (1997)? Please show a range of possible temperatures that can be calculated taking into account different isotope fractionation factors.

We followed this suggestion and used the equation by Kim and O'Neil (1997) to calculate δ^{18}O values for theoretical calcite based on measured water temperatures and the stable isotope composition of modern lake and spring and stream waters nearby. We corrected the resulting values in the text and changed the reference.

Further, we calculated additional $\delta^{18}O$ values (Table 1) for carbonate precipitated from Sidi Ali in equilibrium with host water at specific temperature scenarios and depths using the equation by Kim and O'Neil (1997) as suggested by the reviewer.

The lowest water temperature at the lake bottom in September 2012 was 7.7°C. Here, we have a $\delta^{18}O$ value (water, SMOW) of 1.21 ‰ for the depth of 30 m. Temperatures are quite stable around this depth. Using the Kim and O'Neil (1997) equation results in a $\delta^{18}O$ value (carbonate, VPDB) of 2.55 ‰. (The earlier used equation of Friedman and O'Neil (1977) had resulted in a value of 3.05 ‰, which is not so very different.)

The value of 2.55 ‰ is well within the range of data for the Holocene ostracod shells, which is -1.1 to 8.1 ‰ (min - max). In table 1, we combined measured and assumed temperature scenarios with today's $\delta^{18}O$ values (water, SMOW). For example, we had measured the highest $\delta^{18}O$ value with 2.58 ‰ (water, SMOW) at 5 m water depth in September 2012. Measured temperatures were highest in surface waters and were 19.6°C at maximum. With the exception of one $\delta^{18}O$ (carb) value for assumed 25°C that is slightly lower than our measured range for ostracod shells, all calculated theoretical $\delta^{18}O$ values (carbonate, VPDB) lie between 0.19 and 4.78 ‰ (Table 1) and are in the range of our measured $\delta^{18}O$ values for Holocene ostracod shells at Sidi Ali.

However, we need to keep in mind that ostracod shells are not precipitated in isotopic equilibrium but often show a vital offset of 1 to 2 ‰ due to the metabolism of the animals (von Grafenstein et al., 1999). Therefore, $\delta^{18}O$ values of ostracod calcite are usually 1 to 2 ‰ higher than the assumed values for inorganic calcite. With this in mind, all calculated values in table 1 are within the range of our Holocene ostracod shell data and all these combinations are realistic and cannot be ruled out. The wider range of $\delta^{18}O$ from ostracod shells indicates that Holocene lake water $\delta^{18}O$ was sometimes higher and sometimes lower than today's $\delta^{18}O$ (water) values.

Further, the significantly wider range of Holocene $\delta^{18}O$ values from ostracods (-1.1 to 8.1 ‰) shows that solely water temperature changes cannot explain past $\delta^{18}O$ variability but changes in the precipitation/evaporation ratio must be considered as well. In the fully revised version we consider these issues and refer to Zielhofer et al. 2018b for full details.

Table 1. Calculation of theoretical $\delta^{18}O$ values for carbonates precipitated from Lake Sidi Ali in equilibrium with host water at specific temperatures using the equation by Kim and O'Neil (1997).

Lake water depth	Temp.	$\delta^{18}O$ (water, SMOW)	Theoretical $\delta^{18}O$ (carb., VPDB)	Remarks
30 m	7.7 °C (Sep. 2012)	1.21 ‰ (Sep. 2012)	2.55 ‰	Calculation for actually measured water temperature and $\delta^{18}O$ (water) at 30 m
0 to 5 m	19.6 °C (Sep. 2012)	2.58 ‰ (Sep. 2012)	1.30 ‰	Calculation for maximum measured $\delta^{18}O$ (water) at 5 m depth and maximum surface water temperature (ca. 1 °C warmer than at 5 m)
30 m	4 °C	1.21 ‰ (Sep. 2012)	3.41 ‰	Calculation for assumed coldest water during colder times and present bottom water $\delta^{18}O$ (water)
30 m	4 °C	2.58 ‰	4.78 ‰	Calculation for assumed coldest water during colder times and more evaporated water (similar to surface water)
0 to 5 m	25 °C	1.21 ‰	-1.18 ‰	Calculation for assumed very warm (or shallow) conditions and present bottom water $\delta^{18}O$ (water)

0 to 5 m	25 °C	2.58 ‰	0.19 ‰	Calculation for assumed very warm (or shallow) conditions and today's maximum measured $\delta^{18}O$ (water) at 5 m depth

4) One aspect that has not been discussed is the role of changing water temperatures on ostracod 18O. Particularly during the Early Holocene where the authors argue that there are less cedar trees due to heat stress. There are four phases where there is a clear correlation with the 18O at 10.2, 8.2, 6.0, and 5.2 (I do not see a coherence at 7.3), why are these phases not interpreted as cooler summers? Cooler water temperatures may also result in heavier calcite 18O, and could provide a different interpretation that is consistent with the cedar pollen abundance record. This may also be in line with "Atlantic cooling".

Generally, this is exactly what we said. Increased *Cedrus* pollen indicate cooler summers. However, multi-centennial changes in our $\delta^{18}O$ signal are quite large (more than 2 ‰, e.g. 8.2 ka) and the effect of temperature-dependent stable isotope fractionation during the formation of carbonate in water is not large enough for explaining these large changes. The core location is quite deep, and non-marine ostracods are (with very few exceptions) all benthic. Temperatures in modern Sidi Ali approach 8°C beneath the thermocline at 10-14 m. If temperatures were even as low as 4°C (surely not colder at lake floor because of the density maximum of water at 4°C), $\delta^{18}O$ values could have been not higher than ca. 1 ‰ (see table 1) due to the temperature change. Early Holocene $\delta^{18}O$ fluctuations are often much larger in the record and water temperature alone was surely not driving these fluctuations. Even the slighter variabilities of Late Holocene $\delta^{18}O$ values cannot be inferred from temperature-dependent stable isotope fractionation because the Sidi Ali curve shows lower values during Atlantic cooling. In the fully revised version we consider these issues and refer to Zielhofer et al. 2018b for full details.

5) I do see a possible correlation with the HSG record from Bond et al. for the Early Holocene for the positive 18O peaks around 11.4, 10.2, 8.2. However, for the peaks at 9.3, 7.3, 6.7, 6.0, and 5.2 the variation in the 18O is either very small or the timing is not comparable to the Bond-events. The timing might be due to age-model uncertainties. But in its present form, I'm unable to assess whether the Bond events and the positive peaks in 18O are within error of the age model or not, because the age uncertainties are not indicated in Fig. 2. This is definitely a must.

The age model and age uncertainties were submitted as supplementary online material in the first version of the manuscript. However, we add the error bars in the newly compiled figure (see new Fig. 3e). Further, we add lowpass filters for a better visualisation of "in phase" and "anti-phase" pattern between HSG and $\delta^{18}O$. The filtered records (500yr lowpass filter) show a good match in multi-centennial variability.

6) The 25-point running correlation calculated between the 18O and the Bond record shows correlation that barely reach 0.3, is this significant? Can you draw a line that indicates the 95% confidence level? I'm aware that age model uncertainties should also be taken into account, so this can be discussed.

We checked significance levels. Attained values above 0.4 and below approx. -0.4 are significant (95% confidence level). However, we removed the 25-point correlation in the revised version of the manuscript and argue more carefully ("in phase" vs. "out of phase").

7) During the Late Holocene the authors try to link peaks at 4.6, 4.2, 3.2, 2.7 to peaks in HSG. I truly think that this is very hard to see, because the variation in 18O is very small.

We add lowpass filters for a better visualisation of in phase and anti-phase pattern between δ^{18}O and HSG records (see new Figs. 3c and 3d). The filtered records might provide a better visualisation.

8) The paper shows no figure with a comparison with regional records to test their interpretation of the ostracod 18O record, for example the pollen record from MD95-2043 (Fletcher et al., 2013) should be included. Furthermore, if the authors are correct and their 18O record represents winter precipitation, then a figure with a comparison with NAO records is necessary.

We add a NAO record in the revised manuscript (Fig. 3g; Olsen et al., 2012).

We have doubts about the value of showing MD95-2043 pollen record for comparison. The aim of our paper is to highlight a shift in phasing between δ^{18}O and the Bond (2001) record, and to suggest an explanation for that. For example, during the early Holocene (high summer orbital insolation, residual ice sheets), the Bond Events were associated with strong latitudinal temperature gradient and intensification of the westerly flow and weak penetration of winter rains into the W Mediterranean. During the Late Holocene (weak summer insolation, no ice sheets, modern ocean configuration), the Bond events may be more associated with ocean current changes around the dynamics of the ocean gyres and a similar-to-present linking of cold subpolar Atlantic & NAO-like negative pattern leading to increased rainfall. The MD95-2043 shows some similarities for the early Holocene but shows a slow changing millennial behaviour for the Late Holocene that does not really help support or refute the ideas about centennial variability at Sidi Ali.

Anonymous Referee #2 gave as important suggestions about our proxy data set. We considered his comments in the revised version of our manuscript.

Introduction and methodology: This study leads off with a thoughtful introduction reviewing and analyzing the North Atlantic (NA) rafted debris record (Bond events) and makes a strong case for Mediterranean studies showing probable linkages of hydroclimate and the Bond event record. Studies identified and compared in this work are well summarized, represent a substantial range of Mediterranean sites, and their records compared to highlight regional variability of humidity and dryness, and initially, the authors emphasize caution in attributing these patterns (in response to Atlantic cooling events) to ’forcing mechanisms, or chronological correlations’.

We thank the ref#2 for the general positive comment.

The introduction is bolstered by three well designed figures that present a broad to fine scale descriptions of the study area and place in context the North Atlantic Basin, regional climate patterns, and the coring site depicting the local landscape and vegetation.

We thank the ref#2 for the general positive comment.

The methodology was one of the strengths of this study, with the with addition of 82 new samples to a previously published 18O ostracod record for Lake Sidi Ali in the Middle Atlas range of Morocco. The new samples bring a total number of data points to 182 for 12.97 m record spanning the Early to

Late Holocene (12K cal ybp), and almost doubling the 14C chronological sample resolution of the previous record from “~130 years to 71.4 years”. This robust record is reinforced by 210Pb and 137Cs dating in the historic. The 18O data were further compared with pollen (Cedrus sp.), micro-charcoal, solar activity, solar insolation, as well as a running 25-point correlation between the Bond event IRD record and the Sidi Ali 18O record. Clear figures, stacked with a color overprint of Early to Late Holocene hydroclimate changes and Bond event intervals, strongly reinforce the authors thinking.

We thank the ref#2 for the general positive comment. However, we considered comments of the ref#1 and integrated results of low-pass filtering in the figures. Further, we had to restructure the manuscript according to the comments of the ref#1

Hydroclimate: The authors characterize the overall pattern of the Sidi Ali Record in the Early Holocene with Atlantic cooling coupled with dry winters with higher summer temperatures producing drought stress limiting Cedrus. In addition, the early summer warm climate co-occurs with warm Atlantic winter rains, except during Bond events. The record is dramatically reversed, in this reviewer’s opinion, for the Late Holocene beginning about 5K cal ybp where Atlantic cooling produces wet winters, in a hydroclimate of decreasing rainfall. Both Early and Late Holocene interpretations are supported from additional studies with TOC, diatom, and charcoal; and solar forcing, solar insolation, and chironomid data, respectively. This two-phase change in the Early and Late Holocene 18O record could be described as a marked low frequency, high amplitude signal that sharply decreases in amplitude after 5K cal ybp and the into the Mid-Late Holocene, and arguably begins to increase in amplitude and frequency from ~2K cal ybp into to the modern.

We thank the ref#2 for the general positive comment.

In addressing the 18O record, this reviewer suggests more description and/or insights from the authors would be helpful to interpret and the patterns of the signal with regards to amplitude and frequency, which this reader found dramatic. Possibly presenting these data with some type of signal-to-noise ratio analyses could be helpful.

Many thanks for this comment. Especially we emphasised in the discussion chapter the hydroclimatic change at ~5 ka but also the different frequencies of the d18O and Cedar records.

Additionally, this same approach could be beneficial comparing and evaluating both the pollen and charcoal data. Clearly, there is a wide range of pollen responses between the 10.2 and 7.2 Bond events, using the Early Holocene as an example. And while both responses are positive, they are clearly different in their absolute values, and appear dissimilar. I would find some characterization and analysis of this variability helpful. A similar argument can be made for the Late Holocene segment in the record, again, especially for the charcoal and pollen records. The Late Holocene charcoal signal depicts an increase in peak values of charcoal, and a variable higher frequency pattern of peaks. Some method for identifying fire events, either a threshold of signal to noise ratio, or a confidence interval set from smoothed baseline could potentially sharpen the fire event interpretation.

Many thanks. Actually, we did not follow this suggestion in the overall revision of the manuscript because we had to restructure the manuscript following the issues of ref#1 and put the charcoal record out of the millennial-scale interpretation. Further, in the revised version the Cedrus pollen record is discussed as a probable proxy for summer temperature. We added a 1000 yr low-pass filter for a better illustration of potential coincidences between decreased subtropical summer heat (deMenocal et al. 2000) and Cedrus increases.

Finally, trends in the pollen data, such as the slower rise of Cedrus before the Early/Late Holocene shift in δ18O record, the change in the frequency of the pollen signal, and frequent occurrence of charcoal peaks beginning about 5K cal ybp also suggest there may be additional ecological factors influencing the Cedrus pollen response. Appreciated was the acknowledgment, that settlement history may have had an additional influence in the charcoal record, as is the case with many Holocene paleo-fire reconstructions.

Many thanks. Yes, we add additional thoughts about the ecological factors influencing Cedrus response. Here, the bi-millennial frequency of the Cedrus record might be evident during the Early Holocene due to the generally higher impact of summer solar radiation at that time.

4.2 Bond event: An additional strength of this study was the scholarship involved in the introduction and summary of a wide range of regional studies placing the results of the authors in context with the broader Mediterranean. Especially helpful, was the discussion of hydroclimate variability specific to other environmental reconstructions of the 4.2 period across the Mediterranean. The findings of this study showing a cool wet event at the 4.2 Bond event, was nicely contrasted with a number regional studies mostly indicating the 4.2 as a period of dryness. Further, the thoroughness of the authors placing this study in the context of such a wide spectrum of studies throughout the entire paper, potentially could be improved by a table or matrix figure summarizing this study's results and the many citations included within, bringing readers less familiar with Holocene paleo-environments of the Mediterranean region, into the sphere of thinking of the authors.

We thank the ref#2 for the general positive comment and the helpful suggestion. Right, in the final version of the manuscript we integrated a matrix figure summarising major study's results (Fig. 4).

Conclusions: This is a well written paper, and should be published with minor revisions. The amplification of the resolution of a previously published record, and subsequent interpretation of that record, is an important and detailed contribution to the understanding of paleo-hydroclimate dynamics of Morocco. In addition, the paper makes a significant case for further investigations of Holocene paleo-hydroclimate scenarios in a broader Mediterranean context, with the comparison of this record to numerous efforts, emphasizing "coherence with Bond events across the entire

Holocene" for some areas, yet in contrast, other sites demonstrating a variable step change from a wetter Early Holocene to a Late-Holocene of aridity at 5K cal ybp.

We thank the ref#2 for the general positive comment.

Post-script comments on the author response to Anonymous Reviewer 1: Figure, table, and comments submitted in both responses to Reviewer 1, greatly strengthened this submission. Especially helpful were 2 sigma age model panel, in addressing uncertainties, and the 500-year low pass filter on the pollen record and 18O reconstruction clarifying the Cedrus response.

We thank the ref#2 for the general positive comment.

Dear editor, **you** gave as additional comments and instructions:

Thanks for your patience in awaiting reviews! I find your responses to be helpful and appropriate so please prepare the final revised manuscript with the proposed changes and revised figures as outlined in your responses. It is not clear why you included Usoskin et al in one version of the figure and that does not seem to be very useful, so I suggest leaving that out or explaining its significance.

Right, we removed Usoskin from the final version of figure 2.

Similarly, the TSI plot does not add much to the paper and unless its importance can be explained, I would suggest leaving that out also.

The TSI plot is mentioned in the discussion (page 12 line 25) and we would like to show the record in Fig. 3.

All that being said, I think this is a thoughtful and interesting paper that is appropriate for publication in CoP, and as part of the "Special Issue on the 4.2ka BP event"

Many thanks for your comments and support in editing the manuscript

Kind regards

Christoph Zielhofer and all co-authors

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Western Mediterranean hydro-climatic consequences of Holocene iceberg advances (Bond events)

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Abstract. Gerard C. Bond established a Holocene series of North Atlantic ice rafted debris events based on quartz and hematite stained grains recovered from subpolar North Atlantic marine cores. These so-called ‘Bond events’ document nine large-scale and multi-centennial North-Atlantic cooling phases that might be linked to a reduced thermohaline circulation. Regardless of the high prominence of the Holocene North Atlantic ice rafted debris record, there are critical scientific comments on the study: the Holocene Bond curve has not yet been replicated in other marine archives of the North Atlantic and there exist only very few palaeo-climatic studies that indicate all individual Bond events in their own record. Therefore, evidence for consistent hydro-climatic teleconnections between the subpolar North Atlantic and distant regions is not clear. In this context, the Western Mediterranean region presents key hydro-climatic sites for the reconstruction of a teleconnection with the subpolar North Atlantic. In particular, variability of Western Mediterranean winter precipitation might be the result of atmosphere-ocean coupled processes in the outer-tropical North Atlantic realm.

Based on an improved Holocene δ^{18}O record from Lake Sidi Ali (Middle Atlas, Morocco) we correlate Western Mediterranean precipitation anomalies with North Atlantic Bond events to identify a probable teleconnection between Western Mediterranean winter rains and subpolar North Atlantic cooling phases. Our data show a noticeable similarity between Western Mediterranean winter rain minima and Bond events during the Early Holocene and an opposite pattern during the Late Holocene. There is evidence for an enduring hydro-climatic change in the overall Atlantic atmosphere-ocean system and the response to external forcing during the Mid-Holocene. Regarding a potential climatic anomaly around 4.2 ka (Bond event 3) in the Western Mediterranean, a centennial-scale winter rain maximum is generally in phase with the overall pattern of alternating ‘wet and cool’ and ‘dry and warm’ intervals during the last 5,000 years.

1 Introduction

Gerard C. Bond reconstructed a Holocene series of North Atlantic ice-rafting events (Bond et al. 1997, 2001) based on the numbers of counted quartz and haematite stained grains in marine cores recovered from the subpolar North Atlantic (Fig. 1a). These so-called 'Bond events' document nine (Fig. 3b) large-scale and multi-centennial North-Atlantic cooling phases that might be linked to a reduced thermohaline circulation in the North Atlantic. Due to attested large-scale atmosphere-ocean-linked teleconnections, an increasing number of palaeoclimatologists relate Bond events with chronologically in-phase climatic anomalies all over the world. To this day, the manuscript about North Atlantic ice rafted debris events (Bond et al. 2001) is one of the most cited papers on the Holocene climate history (2756 citations, Google Scholar, 2019).

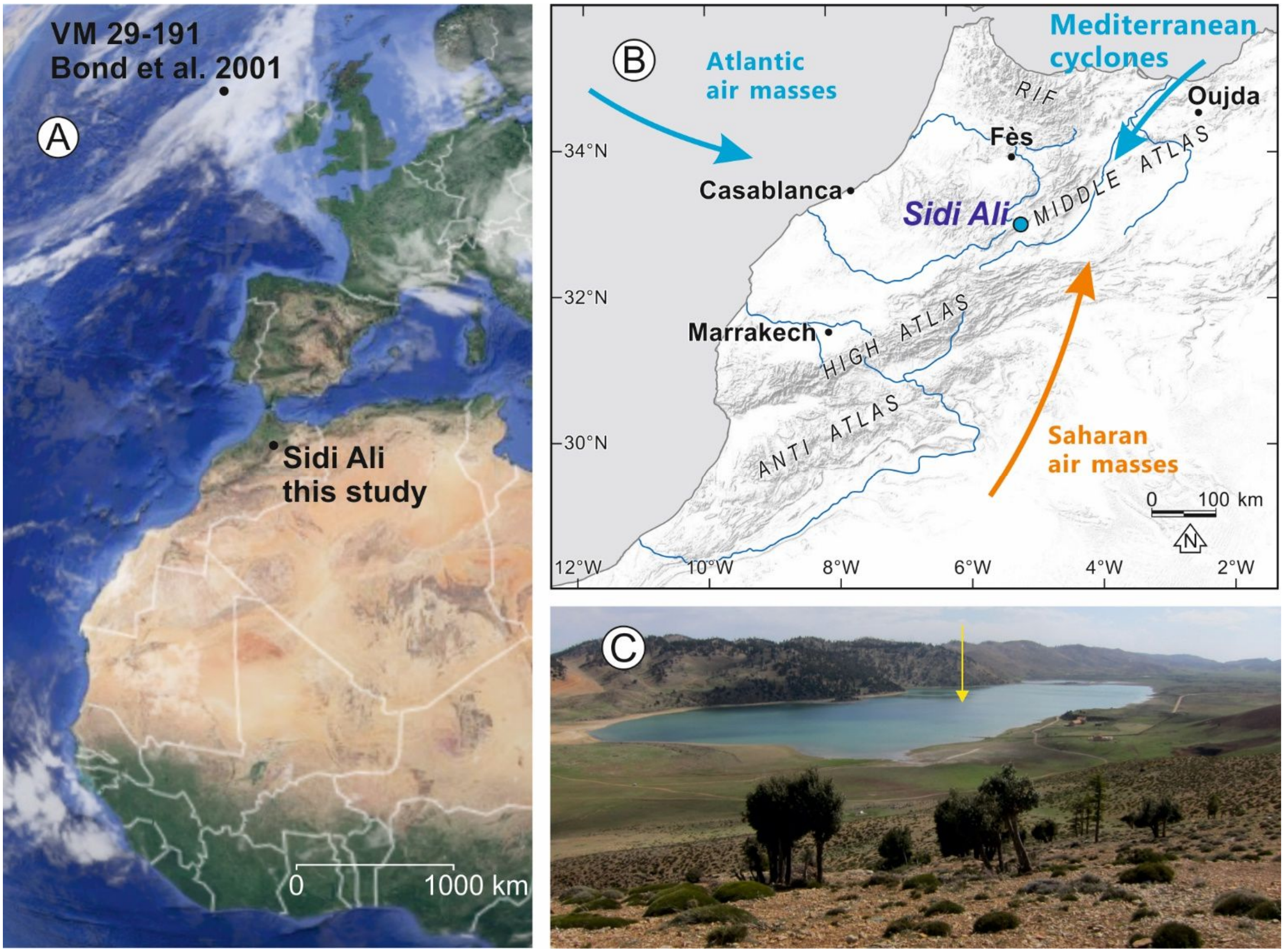

Figure 1: Geographical setting. A) Positions of the stacked ice rafted debris record (MC52 + VM29-191, Bond et al. 2001) and the improved Sidi Ali oxygen stable isotope record (this study); B) Regional context of Lake Sidi Ali in the Moroccan Middle Atlas, arrows indicate impacts of different air masses on Holocene climate history; C) Lake Sidi Ali, the yellow arrow shows the core position.

Regardless of the high prominence of the Holocene North Atlantic ice rafted debris record, there are also numerous critical scientific comments on the study: **a)** As far as the authors are aware, the stacked Holocene Bond curve has not yet been replicated in other marine archives of the North Atlantic, or could not be reconstructed (Bradley and Bakke, 2019). **b)** Some marine geologists question whether sand grains in these marine cores represent lithological material transported by rafted icebergs (Sejrup et al., 2011). **c)** Bond et al. (2001) postulated a quasiperiodic, "1500-year" cycle in the Holocene ice rafted debris record. However, a Holocene 1,500 cycle remains controversial in the scientific community (Darby et al., 2012; Obrochta et al., 2012). **d)** The forcing mechanisms for the multi-centennial to millennial-scale ice rafted debris events are not clear (Bügelmayer-Blaschek et al. 2016). **e)** Furthermore, there exist only very few palaeoclimatic studies (Cheng et al., 2015; Smith et al., 2016) that indicate all individual Bond events in their own record. Therefore, evidence for consistent hydro-climatic teleconnections between the subpolar North Atlantic and distant regions is not clear for the entire Holocene.

In this context, the Western Mediterranean region features key hydro-climatic sites for the reconstruction of a potential teleconnection with the subpolar North Atlantic. Beside indications for synchronous temperature changes in both regions (Català et al, 2018), Western Mediterranean variability of Holocene winter precipitation is the result of large-scale atmosphere-ocean coupled processes in the outer-tropical North Atlantic realm (Lamb et al., 1995; Trouet et al., 2009; Wassenburg et al., 2013, 2016; Zielhofer et al. 2017a). In addition to indications from continuous hydro-climatic archives, Western Mediterranean alluvial archives show a link with Bond events. Fluvial geomorphologists identify Holocene flood intervals that chronologically match with peaks in the ice-rafted debris record. This is the case for Western Mediterranean fluvial records in Morocco and Tunisia (Faust et al., 2004; Zielhofer and Faust, 2008; Zielhofer et al., 2010) but also for fluvial records in Western Mediterranean Europe (Benito et al. 2008; Wolf et al., 2013; Benito et al. 2015a, 2015b). Furthermore, Western Mediterranean proxy data for prehistoric human occupation, such as ^{14}C cumulative probability plots from archaeological databases, show a probable linkage with ice rafted debris events (Zielhofer et al., 2008; Linstädter, 2016).

Although many Western Mediterranean hydro-climatic records attest coincidences with Bond events, the forcing mechanisms and chronological correlations are not clear: **a)** In the Western Mediterranean multiple studies show that Holocene humidity changes are locally variable and of contrasting sign (Morellón et al., 2018). Whereas palaeoecological studies from the Pyrenees indicate environmental conditions that are more humid during Mid- and Late Holocene North Atlantic cooling events (Pélachs et al., 2011), a prominent δ^{18}O speleothem record from Northern Spain (Smith et al., 2016) shows arid intervals. **b)** Standard age errors of ^{14}C and OSL dating techniques but also the non-continuous and non-linear deposition pattern of many terrestrial archives, such as flood deposits (Faust and Wolf, 2017), do not enable accurate age models and a direct synchronisation with Bond events.

In a previous manuscript, we presented a stable oxygen isotope record of Holocene benthic ostracods from Lake Sidi Ali in the Middle Atlas, Morocco that indicates multi-centennial to millennial intervals of Western Mediterranean winter rain minima during the last 12,000 years (Zielhofer et al., 2017a). Here, δ^{18}O maxima correspond with winter rain minima. However, the mean chronological resolution of the previous stable oxygen isotope record is ~130 years and only allows a limited comparison with palaeoecological proxy data from the same core. In the present manuscript, the chronological resolution of the Sidi Ali δ^{18}O record is improved. We aim to compare the higher resolution δ^{18}O data with the published *Cedrus* pollen record from the same core (Campbell et al., 2017). The direct comparison of palaeohydrological and palaeoecological data from the same core enables a multi-proxy interpretation without age uncertainties that allows a better understanding of the Western Mediterranean hydro-climate history. Furthermore, we correlate for the first time the newly established Sidi Ali δ^{18}O record with the North Atlantic ice rafting debris record (Bond et al., 2001) to identify a probable teleconnection between Western Mediterranean winter rains and ocean-atmosphere coupled cooling phases in the subpolar North Atlantic. Finally, we provide an analysis of the Western Mediterranean hydro-climate during the 4.2 ka Climatic Event (Bond event) that is in the focus of the present "Climate of the Past" special issue.

2 Study Area

2.1 Lake Sidi Ali geographical and hydro-climatic setting

The geographical position of the karstic Lake Sidi Ali in the Middle Atlas (33° 03' N, 5° 00' W, 2080 m a.s.l.) is within the mountainous desert margin of Morocco between the subhumid Mediterranean climate in the North and the arid Saharan climate in the South (Fig. 1b). The mean annual precipitation at Lake Sidi Ali is about 430 mm with a mean annual temperature of 10.3°C (mean JJA maximum, 32.5°C; mean DJF minimum, -8.4°C) and a dry season lasting from June to September (Zielhofer et al. 2017b). The current hydro-climate at Sidi Ali is characterised by Atlantic cyclones during the winter season with a strong impact of the present-day North Atlantic Oscillation (NAO) providing more precipitation during NAO negative stages (Hurrell, 1995; Hurrell et al., 2003). In contrast, Mediterranean cyclones are more associated with rainfall during spring and autumn (Knippertz et al., 2003). The surrounding forest vegetation, consisting of evergreen oak (*Quercus rotundifolia*) and Atlantic cedar (*Cedrus atlantica*), is strongly degraded due to overgrazing. The lake lies within a closed basin of approx. 14 km^2 and has a varying surface area between 2.0 and 2.8 km^2 (Sayad et al., 2011). During late summer 2012, Lake Sidi Ali waters had δ^{18}O values between +1.21 and +2.57‰ vs. SMOW, a surface temperature of 18.5°C and a lake bottom temperature of 8.7°C. The surface δ^{18}O values are higher than those of bottom waters indicating the evaporative enrichment during summer stratification.

2.2 Lake Sidi Ali core recovery and chronology

At the deepest part of Lake Sidi Ali our research group conducted a drilling campaign in September 2012 (Fig. 1c). A 19.56 m sequence from a single borehole was recovered using an UWITEC piston corer. The sediments consist of faintly laminated, organic silts with some aquatic macrofossils including ostracods. The sequence is continuous without any hiatus (Zielhofer et al. 2017a). Our Bayesian age model is based on 26 AMS ^{14}C dates on pollen concentrates and terrestrial plant remains and

^{210}Pb and ^{137}Cs radiometric dating (Fletcher et al., 2017). The age model reveals a coherent robust chronology, which provides a continuous record for the last 12,000 years (Fig. S1).

3 Methods: oxygen isotopes of ostracod shells

We add 82 new samples of adult ostracod shell material from the closely related species *Fabaeformiscandona* sp. and *Candona* sp. to improve the chronological resolution of the previous oxygen isotope record (Zielhofer et al., 2017a). For ostracod sampling, 8g dry sediment was freeze-dried and treated with 3 % H_2O_2. Afterwards, the samples were wet-sieved with a mesh size of 250 µm. The residues were dried at 50° C. Then, ostracod shells were picked under a binocular microscope. Four to six adult shells (about 20 µg) were used for oxygen isotope analyses. Shells were reacted with 105 % phosphoric acid at 70 °C using a Kiel IV online carbonate preparation line connected to a MAT 253 mass spectrometer. Reproducibility was checked by replicate analysis of NBS19 and was better than ±0.06 ‰ (1 σ) for δ^{18}O values. Age estimates for the new oxygen isotope data (vs. PDB) were extracted from the existing Sidi Ali age model (Fletcher et al., 2017). Further, we apply 1000 yr and 500 yr lowpass filters (programme PAST) that reduce centennial-scale variabilities of the proxy records.

4 Results and Discussion

The improved Sidi Ali δ^{18}O record (grey lines in Fig. 2a and 3d) consists of 168 data points for the last 12,000 years and provides a mean chronological resolution of 71.4 years. The chronological frame encompasses the entire Holocene and the last 300 years of the Late Glacial. Due to the scattering of the original data, 1000 and 500 yr lowpass filters were applied (black lines in Fig. 2a and 3d) for a better visualisation of the millennial and multi-centennial trends.

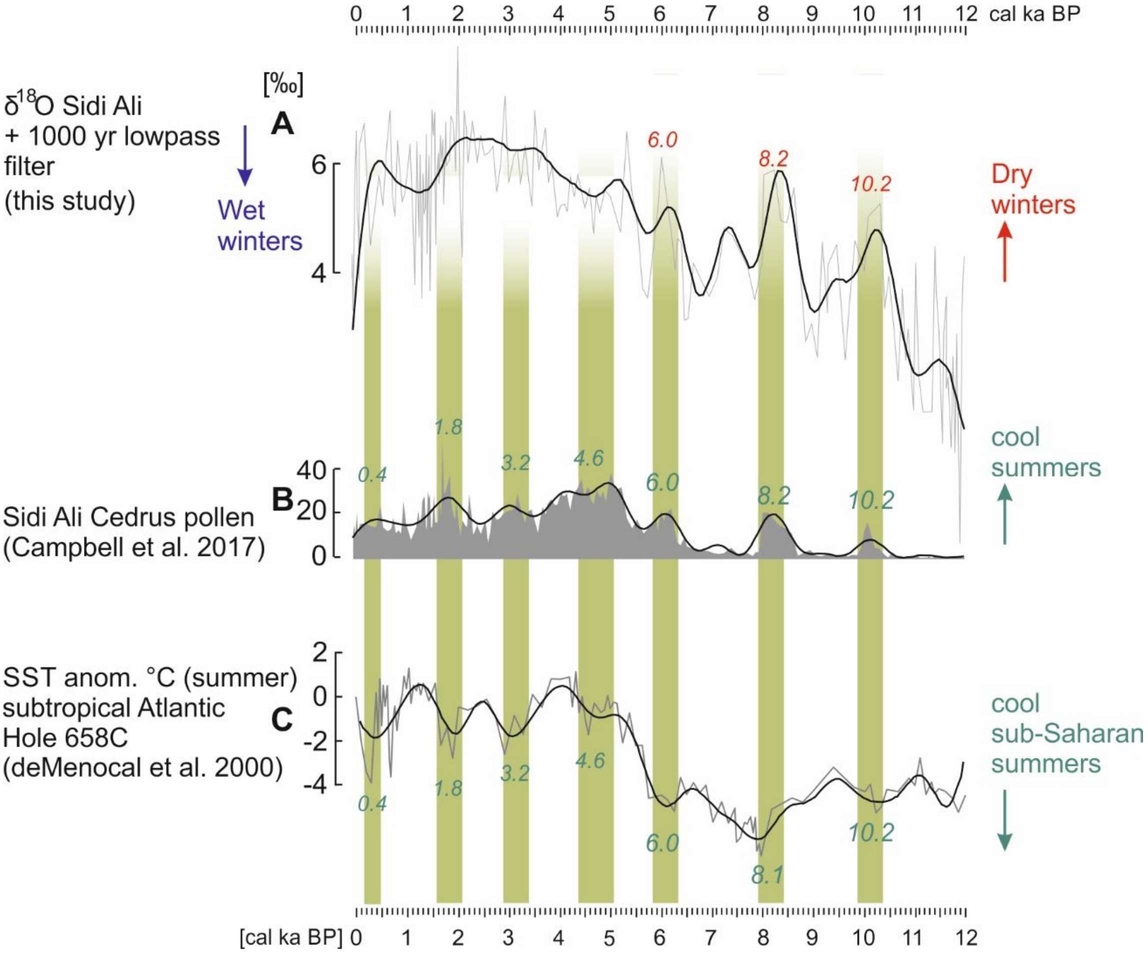

Figure 2. Western Mediterranean (Sidi Ali) winter rain and *Cedrus* records versus a sub-tropical summer temperature record: A) Improved Holocene Sidi Ali $\delta^{18}O$ record from closely related species *Fabaeformiscandona* sp. and *Candona* sp. (Zielhofer et al., 2017a and this study). The grey line represents the original data. The black line shows results of a lowpass filter (1000 year) removing centennial to multi-centennial variability. Red numbers indicate major dry winter phases in the Western Mediterranean; B) Sidi Ali *Cedrus* pollen record (Campbell et al. 2017). The black line shows results of a lowpass filter (1000 year); C) Summer sea surface temperature (SST) at Hole 658C (deMenocal et al., 2000). The grey line represents the original data. The black line shows results of a lowpass filter (1000 year). Olive numbers and pale olive bars indicate synchronous phases of summer cooling in the Middle Atlas (Sidi Ali) and reduced summer SST in the subtropical North Atlantic.

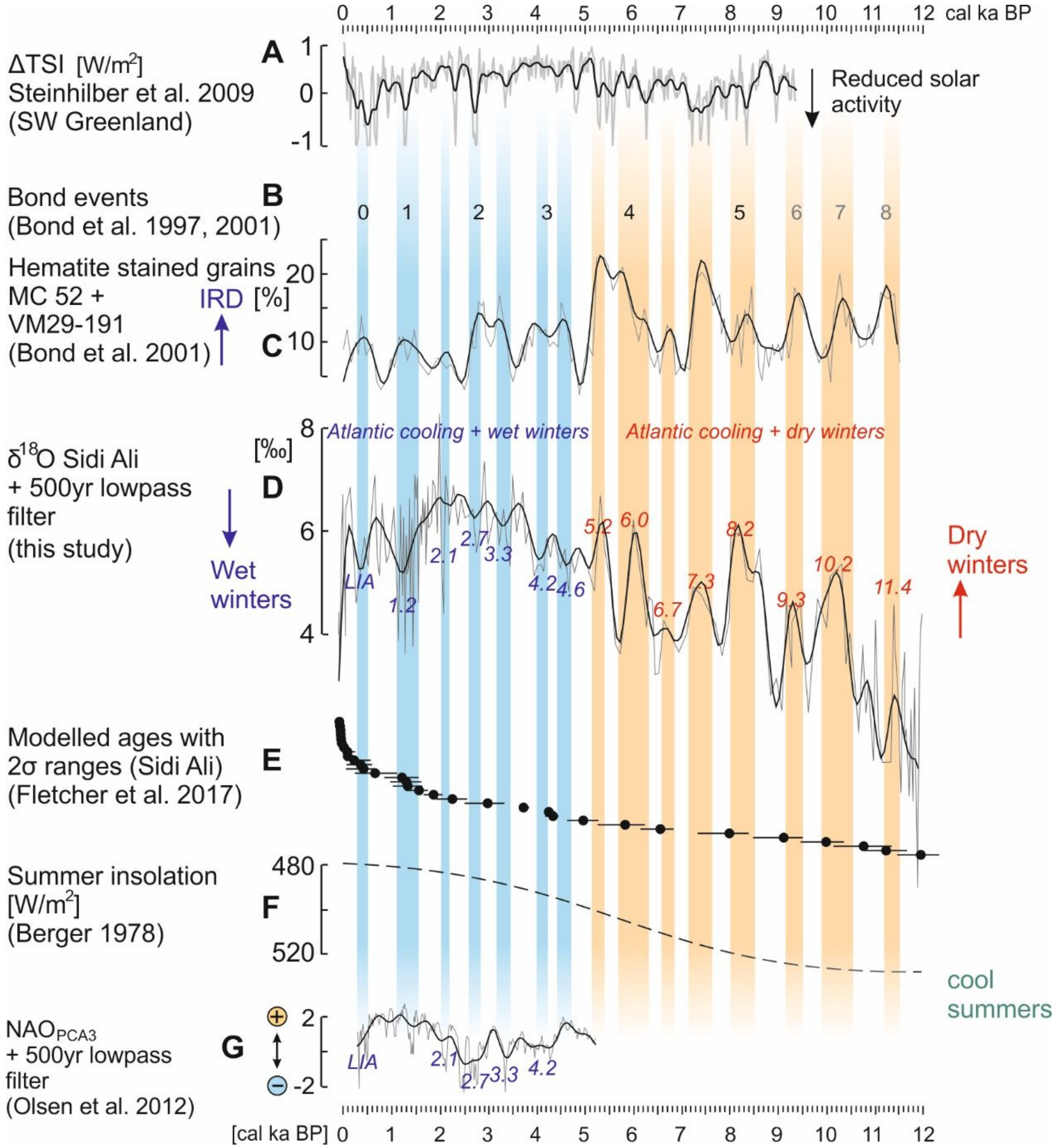

Figure 3. Holocene North Atlantic ice-rafted debris record versus Western Mediterranean (Sidi Ali) winter rain record: A) Total solar irradiance (ΔTSI, Steinhilber et al., 2009); B) Holocene Bond events 0 to 8 derived from Bond et al. (1997, 2001); C) Ice-rafted debris (IRD) record based on hematite stained grains of stacked MC52 and VM29-191 cores from the subpolar North Atlantic (Bond et al. 2001), the black line shows results of a lowpass filter (500 year) removing centennial variability; D) Improved Sidi Ali δ^{18}O record from closely related species *Fabaeformiscandona* sp. and *Candona* sp. (Zielhofer et al., 2017a and this study). The grey line represents the original data. The black line shows results of a lowpass filter (500 year). Blue/red numbers and pale blue/orange bars indicate North Atlantic cooling events and wet/dry winters in the Western Mediterranean; E) Modelled ages with 2 sigma ranges (Fletcher et al., 2017); F) Summer insolation (65°N, June, Berger, 1978) (note reversed axis); G) Palaeo-NAO record (Olsen et al., 2012) with a 500 year lowpass filter.

4.1 Full range of the $\delta^{18}O$ ostracod record from the Sidi Ali core

In consideration of present $\delta^{18}O$ values and temperatures of Lake Sidi Ali waters (Zielhofer et al. 2017a) and according to the equation of Kim and O'Neil (1997), carbonate formed in the modern Lake Sidi Ali waters should have $\delta^{18}O$ values between +1.3 and +2.5 ‰. In contrast, carbonates formed in nearby freshwater springs and streams currently reveal much lower values between -9 and -6 ‰, indicating that the higher values in the lake waters are significantly affected by evaporation (Benkaddour et al., 2005, Zielhofer et al. 2017a). The computed $\delta^{18}O$ values between +1.3 and +2.5 ‰ for carbonates in modern lake waters are slightly lower than the youngest $\delta^{18}O$ value from Sidi Ali ostracod shells that attain +3.8 ‰ likely due to the vital offset of ostracod calcite in comparison to anorganic carbonate (von Grafenstein et al., 1999). The full ostracod record ranges from -1.1 to +8.1 ‰ (Fig. 2a). These $\delta^{18}O$ values were always higher than the computed values of the current freshwater springs, providing evidence for an always closed-basin lake during the recorded period.

We calculated additional $\delta^{18}O$ values for carbonate precipitated from Sidi Ali in equilibrium with host water at specific temperature scenarios and depths using the equation by Kim and O'Neil (1997). As a result, the significantly wider range of Holocene $\delta^{18}O$ values from ostracods (-1.1 to 8.1 ‰) shows that solely water temperature changes cannot explain past $\delta^{18}O$ variability but changes in the precipitation/evaporation ratio must be considered as well. For more details, we refer the reader to Zielhofer et al. (2018b).

Further, we calculated the potential effect of temperature-dependent stable isotope fractionation during the formation of carbonate in Sidi Ali water. As a result, multi-centennial $\delta^{18}O$ changes could have been not higher than ca. 1 ‰ due to temperature changes. However, multi-centennial changes in the Sidi Ali $\delta^{18}O$ signal are relatively large (more than 2 ‰, e.g. 8.2 ka). Therefore, the effect of temperature-dependent stable isotope fractionation is not large enough for explaining these large changes. For more details, we refer the reader to Zielhofer et al. (2018b).

4.2 Western Mediterranean hydro-climate anomalies during the Holocene

Long-term Holocene change of the Sidi Ali $\delta^{18}O$ record

In the Sidi Ali core, the filtered $\delta^{18}O$ values increase from approx. +3 to +5 ‰ in the Early Holocene to values from +5 to +7 ‰ in the Late Holocene (Fig. 2a). As the most straightforward scenario for a subhumid, closed basin (Roberts et al., 2008) this implies a decrease of the precipitation/evaporation ratio with generally more arid conditions towards the Late Holocene. This corresponds with Sidi Ali diatom, TOC and carbonate records that indicate in average higher lake levels during the Early Holocene and lower levels at later stages (Zielhofer et al., 2017a).

These findings seem to contradict the *Cedrus* pollen record from Lake Sidi Ali (Fig. 2b; Campbell et al., 2017) that shows a low or even missing occurrence of cedars during the Early Holocene, indicating reduced moisture availability at that time.

However, reduced moisture availability for the cool-preferring cedar seems to be the result of enhanced summer heat during the Early Holocene. Due to their shallow roots, cedars are vulnerable to summer heat in contrast to the warm tolerant and deep-rooting evergreen oaks that dominate the Sidi Ali pollen record during the Early Holocene (Campbell et al., 2017). In this context, we attest summer temperature-driven drought stress and not winter precipitation as the limiting factor for the long-term trend of Holocene cedar occurrence in the Middle Atlas. This inference is in good agreement with the orbital-forced summer insolation maximum during the Early Holocene (Fig. 3f; Berger 1978) and the chironomid-based summer temperature reconstructions that indicate enhanced Mediterranean summer temperatures during the Early Holocene as well (Samartin et al., 2017).

Following our interpretation, at orbital scale our proxies show enhanced winter precipitation (low $\delta^{18}O$) and enhanced summer heat (low *Cedrus* pollen concentrations) during the Early Holocene and reduced winter precipitation (high $\delta^{18}O$) and cool summer conditions (high concentration of *Cedrus* pollen) during the Late Holocene (Fig. 4: orbital scale). We think that this is currently the best interpretation (Campbell et al. 2017) but alternatives may exist. Furthermore, we worked out that higher $\delta^{18}O$ values might be also the result of a specific origin and seasonality of the precipitation-bearing air masses. We assume that Late Holocene precipitation from springtime Mediterranean cyclones reveal higher $\delta^{18}O$ values than Atlantic winter rains (Zielhofer et al. 2017a). This growing season precipitation would also be favourable for *Cedrus* trees, further helping to explain the apparent contradiction between the long-term trend for the two proxies.

Millennial- to multi-centennial Holocene hydro-climatic variability in the Western Mediterranean

The 1000 yr lowpass filtered Sidi Ali $\delta^{18}O$ record displays noticeable millennial peaks for the last 12,000 years (Fig. 2a). During the Early and first half of the Mid-Holocene bi-millennial $\delta^{18}O$ maxima correspond with occurrences of *Cedrus* pollen (Fig. 2b; Campbell et al., 2017), this is the case at 10.2, 8.2, and 6.0 cal ka BP. Whereas increased $\delta^{18}O$ maxima indicate reduced winter rain, synchronous increases in *Cedrus* pollen are the result of enhanced moisture availability during summer. However, the orbital pattern between Sidi Ali $\delta^{18}O$ and *Cedrus* is not generally visible in the comparison of $\delta^{18}O$ and *Cedrus* records at millennial time scales. We argue that the *Cedrus* record is influenced by summer heat stress and that summer heat might be predominantly forced by the subtropical high and not by North Atlantic air masses. This is visible in the in-phase pattern between subtropical summer SST and our *Cedrus* record at millennial time scales (olive bars in Fig. 2). In contrast, reduced summer heat ("cooling" at Sidi Ali) can be in phase with reduced winter rainfall at Sidi Ali (e.g. 10.2, 8.2 and 6.0 cal ka BP; Figs. 2a and 2b) but there are also indications for out-of-phase patterns (e.g. 9.3 and 7.3 cal ka BP but also during the Late Holocene; Figs. 2a, 2b, and Fig. 4: centennial to millennial scale). Hence, this out-of-phase pattern might be influenced by different forcing mechanisms for summer cooling (sub-tropical high) and winter rain (North Atlantic winter cyclones).

Western Mediterranean winter rainfall anomalies parallel with North Atlantic Bond events

Following the line of arguments above, peaks in the Sidi Ali $\delta^{18}O$ curve are interpreted as North Atlantic derived winter rain minima. This corresponds with noticeable parallels between the Sidi Ali $\delta^{18}O$ curve and the prominent subpolar North Atlantic ice rafted debris record (Bond et al., 2001) from stacked MC52 and VM29-191 marine cores (pale blue/orange bars in Fig. 3). The synchronous pattern supports the idea of a Holocene teleconnection between Western Mediterranean winter precipitation and North Atlantic cooling. We are not able to provide significant correlations between Sidi Ali $\delta^{18}O$ and ice-rafted debris due to different resolutions and probable uncertainties in both age models. However, we applied 500 yr lowpass filters for the Sidi Ali $\delta^{18}O$ curve and the ice-rafted debris record (Figs. 3c and 3d) that indicate a good match between both records. Major peaks in the Early to Mid-Holocene Sidi Ali $\delta^{18}O$ curve coincide with maxima in the ice rafted debris record (orange bars in Fig. 3). This is particularly evident at 11.4, 10.2, 9.3, 8.2 and 6.0 cal ka BP. As shown in Fig. 3b, these prominent peaks correspond with Bond events 8 to 4 (Bond et al., 1997, 2001).

In contrast, there is a noticeable negative relationship between Western Mediterranean winter rain minima and the ice rafted debris record during the Late Holocene. Here, low $\delta^{18}O$ values coincide with peaks in the ice rafted debris record (blue bars in Fig. 3). Major troughs in the Sidi Ali $\delta^{18}O$ curve at 4.2, 2.7, 1.2 cal ka BP and during the Little Ice Age (LIA) concur with Bond events 3 to 0 (Fig. 3b, and Fig. 4: centennial to millennial scale). Hence, the compilation of our $\delta^{18}O$ curve with the ice rafted debris record reveals **a hydro-climatic shift at ~5 cal ka BP** with multi-centennial intervals of Western Mediterranean winter rain minima and North Atlantic cooling during the Early and first half of the Mid-Holocene and opposite phases of winter rain maxima and North Atlantic cooling during the last 5,000 years.

4.3 Evidence for a ‘4.2 ka Climatic Event’ in the Western Mediterranean?

Our manuscript is part of the ‘Climate of the Past’ special issue that addresses the ‘4.2 ka Climatic Event’ and its probable global appearance. According to Weiss (2016), there is evidence for a 4.2-3.9 ka megadrought across the Mediterranean and Western Asia that led to collapses of Early Bronze Age societies. The ‘4.2 ka Climatic Event’ might correspond with North Atlantic Bond event 3 and there exists an ongoing debate in the scientific community about the global extent of a cold, dry and dusty multi-centennial event at that time. Central European palaeo-climatic archives, such as the well-dated Spannagel Cave speleothems in the Central Alps provide evidence for a cold and winter-dry climate around 4.2 ka (Mangini et al., 2007; Fohlmeister et al., 2012). Furthermore, in Central and southern Italy many speleothems and pollen records indicate a cold and dry climate around 4.2 ka (Margaritelli et al., 2016; Zanchetta et al., 2016; Di Rita and Magri, 2019). However, Western Mediterranean palaeo-environmental archives do not show uniform climatic patterns around 4.2 ka (Bini et al., 2018), although multiple studies report an arid interval at that time: in north-eastern Spain a prominent speleothem record indicates cold and dry conditions around 4.2 ka. According to Smith et al. (2016), this noticeable arid interval is synchronous with large-scale North Atlantic cooling and an indicator for extending the spatial influence of the above mentioned 4.2 ka megadrought to the Western Mediterranean, or indeed into the Atlantic sector of the Iberian Peninsula. In southern Spain, another speleothem record reveals a micro-hiatus at 4.16 ka that might correspond with the 4.2 ka Climatic Event (Walczak et al., 2015). These findings are supported by a pollen record from the Doñana National Park in south-western Spain that indicates a multi-centennial aridification trend centred at 4.0 cal ka BP (Jiménez-Moreno et al., 2015). Furthermore, a speleothem record from Gueldaman Cave in Northern Algeria reveals a multi-centennial dry phase in Western Mediterranean North Africa that started around 4.4 ka, and was synchronous with abandonment of the cave (Ruan et al., 2016). However, δ^{18}O and δ^{13}C records of an adjacent speleothem at Gueldaman Cave do not show the same pattern and speleothem hydrochemistry might reflect also local factors. In contrast to the authors above, Cruz et al. (2015) assume a centennial-scale wet period at 4.2 ka from the Kaite Cave stalagmite record in Cantabrian Mountains of Northern Spain. Further, there is evidence for increased storm activity in the Mediterranean basin between 4.4 and 4.0 cal ka BP (Sabatier et al., 2012; Kaniewski et al., 2016, Marriner et al., 2017, Bini et al., 2018) that might indicate an enhanced incursion of humid air masses from the North Atlantic at that time.

According to our interpretation of Sidi Ali δ^{18}O values (Fig. 3d) and corresponding ice-rafted debris signals (Fig. 3b), a centennial-scale interval of cool and wet conditions (pale blue bar in Fig. 3) represents the ‘4.2 ka Climatic Event’ in the Middle Atlas. We point out that the Sidi Ali ^{14}C age model of the 4.2 cal ka BP core section is based on two terrestrial plant residues (Fig. 3e, Fletcher et al., 2017) excluding potential age uncertainties due to hard water effects. Overall, this cool and wet interval fits into the in-phase hydro-climatic alternation of ‘cool and wet’ and ‘warm and dry’ conditions during the last 5,000 years in the Western Mediterranean (pale blue bars in Fig. 3). Therefore, the Sidi Ali record shows no dry event, respectively no out-of-phase climatic anomaly but increased humidity at 4.2 cal ka BP simultaneous with North Atlantic cooling.

4.4 Drivers of the Holocene hydro-climate in the North Atlantic-Western Mediterranean region

Forcing mechanisms of Early Holocene Bond events and winter rain minima

During the Early Holocene millennial-scale Sidi Ali winter rain minima parallel North Atlantic Bond events 8 to 4 (orange bars in Fig. 3). Sidi Ali winter rain minima correspond with pollen-derived dry events in the Western Mediterranean lowlands (Fletcher et al., 2013), indicating a noticeable teleconnection between Western Mediterranean decreases in rainfall and North Atlantic cooling. Here, cooling over the North Atlantic was probably associated with a northward shift of Atlantic cyclone trajectories, leading to increased drought in the Western Mediterranean and Northern Africa (Zielhofer et al., 2017a). According to Bond et al. (2001) and Fletcher et al. (2013), North Atlantic cooling episodes, respectively ice rafted debris events result from millennial-scale weakening of the Atlantic Meridional Overturning Circulation (AMOC). Two of these ‘cold relapses’ (Wanner et al., 2011) correspond with prominent freshwater outbursts from the Laurentide ice sheet at 9.3 and 8.2 cal ka BP (Alley and Ágústsdóttir, 2005; Fleitmann et al., 2008), indicating evidence for an AMOC pattern during the deglaciation (Fletcher et al., 2013; Wassenburg et al., 2016) that is comparable with glacial conditions (Rahmsdorf, 2002; Moreno et al., 2005). The Early Holocene periodicity of 900 to 1,000 years in North Atlantic temperature changes and Western Mediterranean humidity is a widespread phenomenon in other palaeo-climatic records (Zhao et al., 2010; Cléroux et al., 2012;

Fletcher et al., 2013, Ramos-Romána et al., 2018) providing a coherence with the Eddy frequency band of total solar irradiance (Steinhilber et al., 2009).

Forcing mechanisms of Late Holocene Bond events and winter rain maxima

Atlantic winter cyclones and Western Mediterranean lows during spring control the present rainfall regime at Lake Sidi Ali in the Middle Atlas (Knippertz et al., 2003). Especially during the winter season, cool and wet air masses of the North Atlantic westerly circulation dominate the present hydro-climate in the Western Mediterranean basin (Born et al. 2010). Currently, the NAO significantly affects the amount of winter rainfall in the Western Mediterranean basin with increases in winter rainfall under negative NAO indices (Hurrell et al. 2003).

Likewise, there are multiple indications that the NAO represents a major forcing mechanism for past hydro-climatic changes in the Western Mediterranean. Both instrumental (Dünkeloh and Jacobeit 2003; Deininger et al. 2017) and also Late Holocene data (Magny et al. 2003; Baker et al., 2015; Corella et al., 2016; Wassenburg et al. 2016; Di Rita et al. 2018a, 2018b) provide evidence for spatio-temporal coherency in European precipitation pattern. Here, negative NAO indices correspond with increased effective winter rainfall in the southwestern Mediterranean and with decreased humidity in the southern Central Mediterranean and in Scandinavia. Following multiple authors (Trouet et al., 2009; Wassenburg et al., 2013), one of the most prominent negative NAO stages during the last 1,000 years occurred during the Little Ice Age. The Sidi Ali $\delta^{18}O$ winter rain curve (Fig. 3d) shows similarities with a lake sediment record from southwestern Greenland (Fig. 3g; Olsen et al., 2012) that represents a NAO reconstruction over the past 5,200 years. Here, low NAO stages of the filtered Olsen record around 4.2, 3.3, 2.7, 2.1 cal ka BP and during the Little Ice Age correspond with winter rain peaks at Sidi Ali.

In this context, Late Holocene North Atlantic cooling and associated winter rain maxima (blue bars in Fig. 3) might reflect coupled atmosphere-ocean variability including subtropical gyre strength changes (Morley et al., 2011, Jalali et al. 2018) that are paced by solar minima (Moffa-Sánchez et al., 2014). Here, Western Mediterranean winter rain maxima (Fig. 3d) coincide with multiple centennial-scale solar minima during the Late Holocene (Fig. 3a). This might be comparable with present NAO pattern that features primarily negative NAO indices during reduced solar irradiance (Matthes, 2011).

However, multi-centennial-scale shifts in Western Mediterranean hydro-climate and North Atlantic hydrography also show spatial differences that do not correspond with current NAO pattern: the International Ice Patrol's counts of icebergs crossing 48 ° N in southern direction are noticeably increased during positive indices of the NAO (Andrews 2000, USCG 2016). In this context, present iceberg variability is predominantly caused by fluctuation in Greenland ice sheet calving discharge rather than open ocean iceberg melting (Bigg et al. 2014). This does not correspond with the pairing of Bond's maxima in ice rafted debris and Sidi Ali winter rain maxima that would reflect negative NAO-like indices during the Late Holocene. Furthermore, Late Holocene ice rafted debris records from multiple North Atlantic marine cores (Bond et al., 2001) reveal synchronous iceberg advances off Newfoundland, off Ireland and off Iceland. Bond's comparison with secondary palaeo-climatic records from the North Atlantic realm indicates that multi-centennial ice rafted debris events correspond with cooling phases in the entire region. This is not in accordance with the typical negative-NAO temperature pattern that shows sub-regional temperature increases in the subpolar North Atlantic (Bond et al., 2001). Spatially synchronous events of Holocene ice rafted debris can be more typical for a reduced North Atlantic Deep Water formation (Moffa-Sánchez and Hall, 2018). In this context, the paleoceanographic evidence for large-scale synchronous Holocene cooling events in the subpolar North Atlantic was recently verified by modelling results (Liu et al., 2017): a reduction of the AMOC corresponds with a widespread cooling over the northern North Atlantic and a noticeable sea ice expansion over the Greenland-Iceland-Norwegian seas.

In summary, the following conclusions for Late Holocene Bond events and Western Mediterranean winter rain maxima result: the Late Holocene coincidence of Sidi Ali $\delta^{18}O$ winter rain maxima and ice rafted debris events does not show strict spatial pattern and mechanisms of the present NAO. Rather, this centennial-scale pattern seems to be more typical for long-term AMOC variability with predominantly southward shifted westerlies and synchronous iceberg advances during intervals of reduced AMOC (Deininger et al., 2017). Here, major Late Holocene cooling events and Western Mediterranean winter rain maxima might correspond with centennial-scale solar minima (Fig. 3a; Steinhilber et al. 2009). Therefore, available 'NAO' reconstructions (Trouet et al. 2009; Olsen et al. 2012; Wassenburg et al. 2016) might reflect a more complex set of forcing mechanisms (ice rafting, AMOC, solar forcing, NAO) influencing decadal to multi-centennial-scale changes in the North Atlantic hydro-climate during the past. Therefore, our improved Sidi Ali $\delta^{18}O$ winter rain record does not represent a strict NAO reconstruction but a hydro-climatic response of multi-centennial to millennial shifts in North Atlantic hydrography.

Mid-Holocene hydro-climatic shift in the Western Mediterranean region

Overall, the noticeable match between the Sidi Ali $\delta^{18}O$ and the ice rafted debris records indicates a Holocene teleconnection between the subpolar North Atlantic and the Western Mediterranean hydro-climate but with a noticeable change in large-scale ocean-atmosphere coupled climatic mechanisms at ~5 cal ka BP. In contrast, some palaeoclimatic studies from the east of the Iberian Peninsula (Pélachs et al. 2011; Smith et al., 2016) but also from the Alpine region (Mangini et al., 2007, Fohlmeister et al., 2012) postulate with reference to Bond's ice rafted debris record consistent oceanic-atmospheric interactions between the subpolar North Atlantic and Western Europe for the entire Holocene. However, high-resolution speleothem records from Southern Spain (Walczak et al., 2015) and the Middle Atlas (Wassenburg et al. 2016), Tunisian alluvial records (Zielhofer and Faust, 2008) and an Alboran Sea pollen record (Fletcher et al. 2013) provide indications for a large-scale hydro-climatic shift in the North Atlantic-Western Mediterranean region during the Mid-Holocene. This Mid-Holocene shift in Western Mediterranean hydro-climate is visible in significant frequency changes in humidity at multi-centennial time-scales but also at orbital scale. There is evidence for Early Holocene humidity and Late Holocene aridity in Mediterranean Morocco (Ibouhouten et al., 2010; Limondin-Lozouet et al., 2013), in central Mediterranean domains of North Africa (Bosmans et al., 2015; Wu et al. 2017) and in the Levant (Migowski et al., 2006, Zielhofer et al., 2018a). Increased Early Holocene rainfall in the

Mediterranean basin corresponds with the African Humid Period in the North African monsoon domain (Bosmans et al., 2015; Shanahan et al., 2015) and reduced Saharan dust supply (Ehrmann et al., 2017; Zielhofer et al. 2017b). The Mid-Holocene southward shift of the ITCZ corresponds with a weakening and northward shift of the Atlantic winter storm tracks (Black et al., 2011; Kutzbach et al., 2014) and led to enduring drier winters in the Mediterranean basin during the Late Holocene.

5 Conclusions

Lake Sidi Ali is situated in the subhumid Middle Atlas Mountains of Morocco. Currently, the local hydro-climate is under strong influence of the NAO that provides enhanced effective rainfall under negative NAO indices. Previous palaeolimnological and -climatological studies indicate that the Middle Atlas represents a key region for Holocene hydro-climatic variability in the Western Mediterranean.

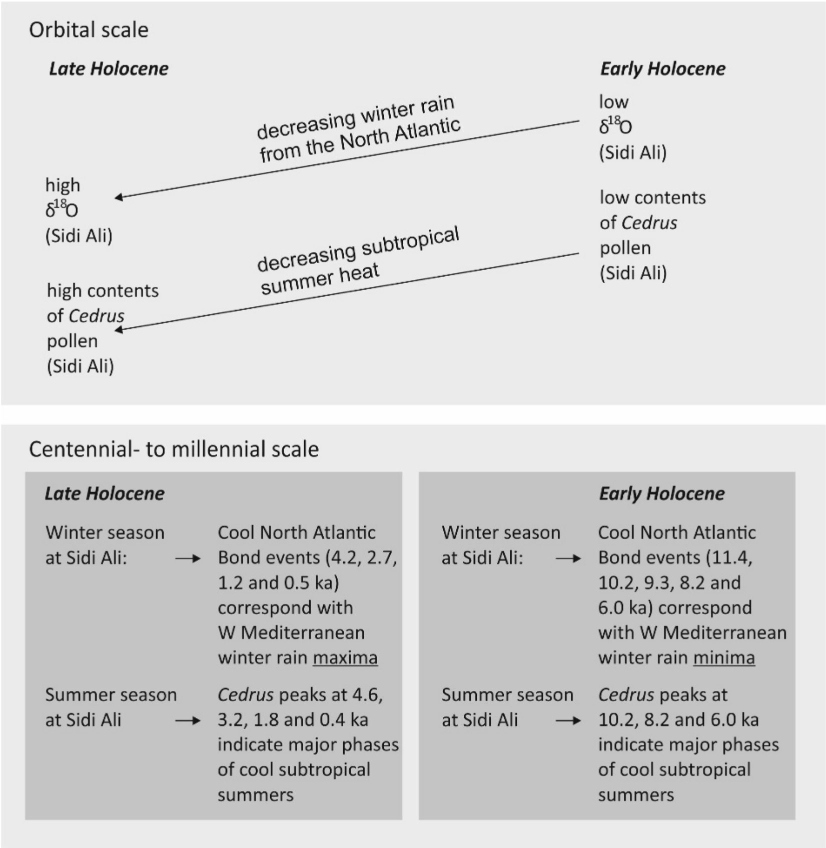

Figure 4. Holocene Lake Sidi Ali record: major conclusions of this study

In this study, we present an improved Holocene δ^{18}O record of Sidi Ali ostracod shell material to enhance the chronological resolution of a previous record from the same core. The new data set provides a mean chronological resolution of 71.4 years. The comparison of the Sidi Ali δ^{18}O record with a *Cedrus* record from the same core (Campbell et al, 2017) shows at orbital scale enhanced winter precipitation (low δ^{18}O) and enhanced summer heat (low *Cedrus* pollen concentrations) during the Early Holocene and reduced winter precipitation (high δ^{18}O) and cool summer conditions (high concentration of *Cedrus* pollen) during the Late Holocene (Fig. 4). At millennial-scale the Sidi Ali δ^{18}O and the *Cedrus* records are in-phase at 10.2, 8.2 and 6.0 cal ka BP but there are also indications for out-of-phase patterns (e.g. at 9.3 and 7.3 ka and during the Late Holocene) (Fig. 4). We argue that this out-of-phase pattern might be influenced by different forcing mechanisms for summer cooling (sub-tropical high) and winter rain (North Atlantic winter cyclones).

Centennial to millennial scale peaks in the Sidi Ali δ^{18}O record represent intervals of Western Mediterranean winter rain minima. The comparison of the Sidi Ali δ^{18}O record with the stacked ice rafted debris record (Bond et al. 2001) from the subpolar North Atlantic indicates a positive coupling during the Early Holocene and an opposite pattern during the Late Holocene. Early Holocene Bond events, respectively North Atlantic cooling, parallel with arid conditions in the Western Mediterranean (Fig. 4), whereas during the last 5,000 years Bond events correspond with wet hydro-climates (Fig. 4). In the Early Holocene at least two Bond events at 9.3 and 8.2 cal ka BP coincide with prominent freshwater outbursts from the Laurentide ice sheet.

Centennial-scale hydro-climatic anomalies show similarities with NAO pattern during the Late Holocene. However, our Sidi Ali δ^{18}O record does not represent a strict NAO reconstruction but rather a hydro-climatic response of multi-centennial shifts in North Atlantic hydrography. Here, solar minima, iceberg advances, subtropical gyre strength changes and a reduced AMOC represent drivers of a coupled North Atlantic ocean-atmosphere system with multi-centennial intervals of Western Mediterranean winter rain maxima during the last 5,000 years.

Focusing on the '4.2 ka Climatic Event' that is a major subject of this 'Climate of the Past' special issue, the data show a cool and wet interval around 4.2 cal ka BP. This is overall in-phase with centennial-scale climatic shifts from 'cool and wet' towards 'warm and dry' hydro-climates during the last 5,000 years in the Western Mediterranean.

Data availability: The newly conducted Sidi Ali oxygen stable isotope record will be provided in open access mode at https://www.researchgate.net/ after the final acceptance of the manuscript. In case of scientific use of the data, the citation of the primary source is obligatory: Zielhofer, C., Köhler, A., Mischke, S., Benkaddour, A., Mikdad, A. and Fletcher, W.J.: Hydro-climatic consequences of Holocene North Atlantic ice rafting events (Bond events) in the Western Mediterranean. Clim. Past., 2019.

Supplement link: Figure S1. Bayesian age model of the Sidi Ali core (Fletcher et al., 2017): the black dots show conventional ^{14}C ages [BP]. The light greyish curves show ^{14}C calibrated ages (prior). The dark greyish curves show modelled age distributions (posterior). The light purple area show the 95% probability distribution. Calibration (2 sigma) of the conventional radiocarbon ages was performed using intcal13.14c.

Author contribution: CZ and WF designed the study; CZ and AK wrote a first draft of the manuscript; AK performed the statistical analyses and undertook the ostracod sampling; SM supervised the ostracod sampling procedure; CZ, AK, SM, AB, AM and WF contributed to discussion and revision of the manuscript.

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

Special issue statement: The authors submit this contribution to the Climate of the Past Special Issue "“The 4.2ka BP Climatic Event”. The manuscript focuses on a newly conducted Holocene oxygen stable isotope record of hydro-climatic variability in the Western Mediterranean that includes a multi-proxy interpretation about a potential hydro-climatic anomaly around the 4.2ka BP Climatic Event.

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