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Western Mediterranean hydro-climatic consequences of Holocene ice-rafted debris (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 haematite-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 palaeoclimatic studies that indicate all individual Bond events in their own record. Therefore, evidence of 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 in 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 $\delta^{18}O$ 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 of an enduring hydro-climatic change in the overall Atlantic atmosphere–ocean system and the response to external forcing during the Middle 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 5000 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 paper about North Atlantic ice-rafted debris events (Bond et al.,

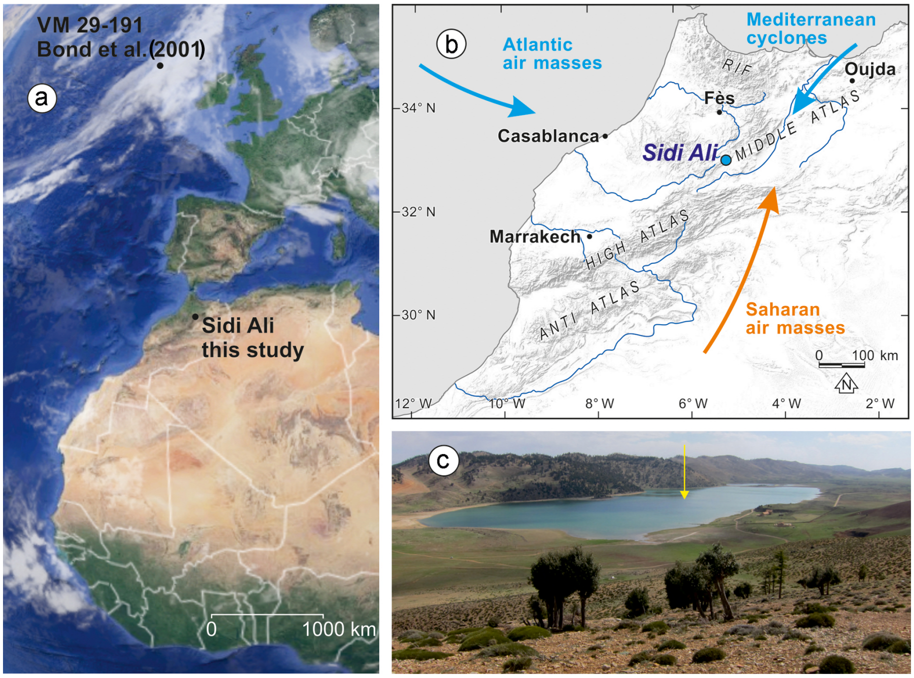

Figure 1. Geographical setting. **(a)** Positions of the stacked ice-rafted debris record (MC52 + VM29-191, Bond et al., 2001) and the improved Sidi Ali oxygen stable isotope record (this study). **(b)** Regional context of Lake Sidi Ali in the Moroccan Middle Atlas; arrows indicate impacts of different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

2001) is one of the most-cited papers on the Holocene climate history (2756 citations, Google Scholar, 2019: https://scholar.google.de/scholar?hl=de&as_sdt=0\T1\textbackslash%2C5&q=Persistent+solar+influence+on+North+Atlantic+climate+during+the+Holocene&btnG).

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 1500-year 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 of 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 of synchronous temperature changes in both regions (Català et al., 2018), Western Mediterranean variability in 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, 2015a, b; Wolf et al., 2013). 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 Middle and Late Holocene North Atlantic cooling events (Pélachs et al., 2011), a prominent $\delta^{18}O$ speleothem record from northern Spain (Smith et al., 2016) shows arid intervals. (b) Standard age errors of ^{14}C and optically stimulated luminescence (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 paper, 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, $\delta^{18}O$ maxima correspond to winter rain minima. However, the mean chronological resolution of the previous stable oxygen isotope record is $\sim$ 130 years and only allows a limited comparison with palaeoecological proxy data from the same core. In the present paper, the chronological resolution of the Sidi Ali $\delta^{18}O$ record is improved. We aim to compare the higher-resolution $\delta^{18}O$ data with the published *Cedrus* pollen record from the same core (Campbell et al., 2017). The direct comparison of palaeo-hydrological 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 $\delta^{18}O$ 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 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 associated more 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 approximately 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 $\delta^{18}O$ values between +1.21 ‰ and +2.57 ‰ vs. Vienna Standard Mean Ocean Water (VSMOW), a surface temperature of 18.5 °C, and a lake bottom temperature of 8.7 °C. The surface $\delta^{18}O$ 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 a 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 accelerator mass spectrometry (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 in the Supplement).

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, 8 g 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 ‰ (1σ) for $\delta^{18}O$ values. Age estimates for the new oxygen isotope data (vs. Vienna Pee Dee Belemnite, VPDB) were extracted from the existing Sidi Ali age model (Fletcher et al., 2017). Further, we apply 1000- and 500-year low-pass filters (programme PAST) that reduce centennial-scale variabilities of the proxy records.

4 Results and discussion

The improved Sidi Ali $\delta^{18}O$ record (grey lines in Figs. 2a and 3d) consists of 168 data points for the last 12 000 years

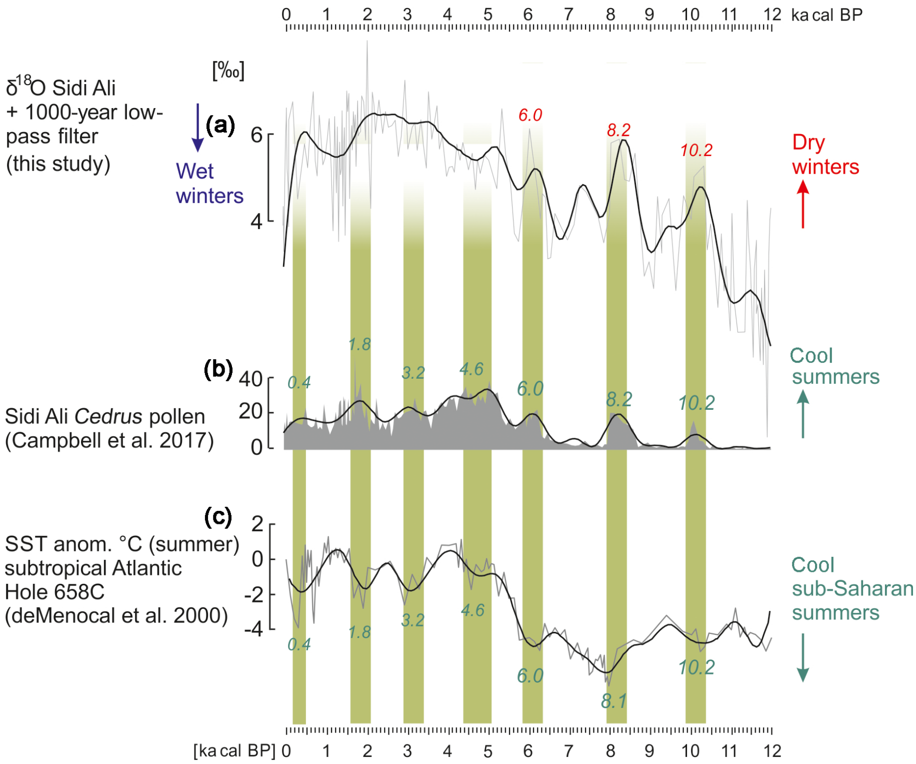

Figure 2. Western Mediterranean (Sidi Ali) winter rain and *Cedrus* records versus a subtropical summer temperature record. **(a)** Improved Holocene Sidi Ali δ^{18}O record from closely related species *Fabaeformiscandona* sp. and *Candona* sp. (Zielhofer et al., 2017a and this study). The grey line represents the original data. The black line shows results of a low-pass filter (1000 years) 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 low-pass filter (1000 years). **(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 low-pass filter (1000 years). 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.

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-year low-pass filters were applied (black lines in Figs. 2a and 3d) for a better visualisation of the millennial and multi-centennial trends.

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

In consideration of present δ^{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 δ^{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 δ^{18}O values between +1.3 ‰ and +2.5 ‰ for carbonates in modern lake waters are slightly lower than the youngest δ^{18}O value from Sidi Ali ostracod shells that attain +3.8 ‰ likely due to the vital offset of ostracod calcite in comparison to inorganic carbonate (von Grafenstein et al., 1999). The full ostracod record ranges from −1.1 ‰ to +8.1 ‰ (Fig. 2a). These δ^{18}O values were always higher than the computed values of the current freshwater springs, providing evidence of a lake that was always a closed basin during the recorded period.

We calculated additional δ^{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 δ^{18}O values from ostracods (−1.1 ‰ to 8.1 ‰) shows that water temperature changes alone cannot explain past δ^{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 δ^{18}O changes could not have been higher than ca. 1 ‰ due to temperature changes. However, multi-centennial changes in the Sidi Ali δ^{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 to explain 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

4.2.1 Long-term Holocene change of the Sidi Ali δ^{18}O record

In the Sidi Ali core, the filtered δ^{18}O values increase from approximately +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 in the precipitation / evaporation ratio with generally more arid conditions towards the Late Holocene. This corresponds to Sidi Ali diatom, total organic carbon (TOC) and carbonate records that indicate on 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), which 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 cedar, which prefers a cool climate, 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 deep-rooting evergreen oaks tolerant to warmth 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 orbitally 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 an orbital scale our proxies show 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: 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 δ^{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 reveals higher δ^{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.

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

The 1000-year low-pass-filtered Sidi Ali δ^{18}O record displays noticeable millennial peaks for the last 12 000 years (Fig. 2a). During the Early and first half of the Middle Holocene, bi-millennial δ^{18}O maxima correspond to occurrences of *Cedrus* pollen (Fig. 2b; Campbell et al., 2017), this is the case at 10.2, 8.2 and 6.0 ka cal BP. Whereas increased δ^{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 δ^{18}O and *Cedrus* is not generally visible in the comparison of δ^{18}O and *Cedrus* records at millennial timescales. 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 sea surface temperature (SST; Fig. 2c; deMenocal et al., 2000) and our *Cedrus* record at millennial timescales (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 ka cal BP; Fig. 2a and b), but there are also indications of out-of-phase patterns (e.g. 9.3 and 7.3 ka cal BP and also during the Late Holocene; Figs. 2a, b and 4: centennial to millennial scale). Hence, this out-of-phase pattern might be influenced by different forcing mechanisms for summer cooling (subtropical high) and winter rain (North Atlantic winter cyclones).

4.2.3 Western Mediterranean winter rainfall anomalies parallel with North Atlantic Bond events

Following the line of argument above, peaks in the Sidi Ali δ^{18}O curve are interpreted as North Atlantic-derived winter rain minima. This corresponds to noticeable parallels between the Sidi Ali δ^{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 δ^{18}O and ice-rafted debris due to different resolutions and probable uncertainties in both age models. However, we applied 500-year low-pass filters for the Sidi Ali δ^{18}O curve and the ice-rafted debris record (Fig. 3c

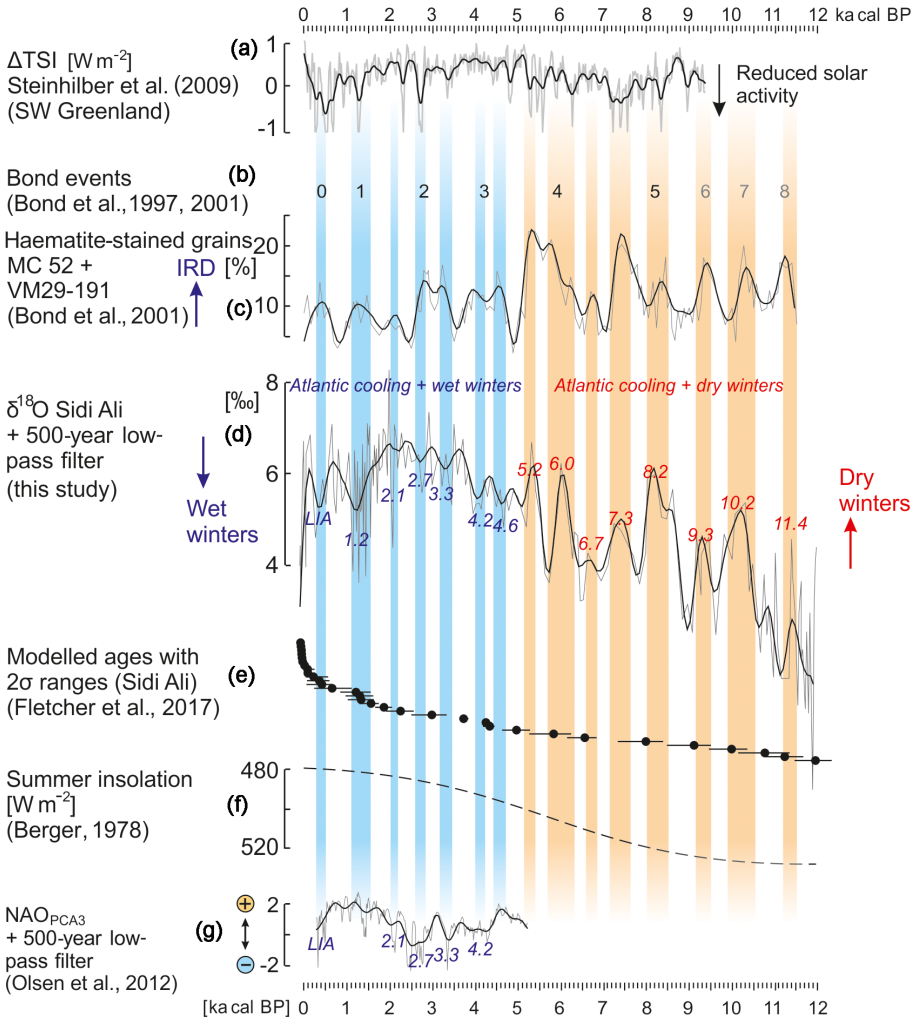

Figure 3. Holocene North Atlantic ice-rafted debris record versus Western Mediterranean (Sidi Ali) winter rain record. **(a)** Total solar irradiance (ΔTSI; Steinhilber et al., 2009). **(b)** Holocene Bond events 0 to 8 derived from Bond et al. (1997, 2001). **(c)** Ice-rafted debris (IRD) record based on haematite-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 low-pass filter (500 years) removing centennial variability. **(d)** Improved 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 low-pass filter (500 years). 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 2σ 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 low-pass filter.

and d), which indicate a good match between both records. Major peaks in the Early to Middle 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 ka cal BP. As shown in Fig. 3b, these prominent peaks correspond to 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 and 1.2 ka cal BP and during the Little Ice Age (LIA) concur with Bond events 3 to 0 (Figs. 3b and 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 $\sim$ 5 ka cal BP with multi-centennial intervals of Western Mediterranean winter rain minima and North Atlantic cooling during the Early and first half of the Middle Holocene and opposite phases of winter rain maxima and North Atlantic cooling during the last 5000 years.

4.3 Evidence of a 4.2 ka climatic event in the Western Mediterranean?

Our paper 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 of 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 to 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 palaeoclimatic archives, such as the well-dated Spannagel Cave speleothems in the Central Alps provide evidence of 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 northeastern 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 of 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 to the 4.2 ka climatic event (Walczak et al., 2015). These findings are supported by a pollen record from the Doñana National Park in southwestern Spain that indicates a multi-centennial aridification trend centred at 4.0 ka cal 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 northern Africa that started around 4.4 ka and was synchronous with the abandonment of the cave (Ruan et al., 2016). However, $\delta^{18}O$ and $\delta^{13}C$ records of an adjacent speleothem at Gueldaman Cave do not show the same pattern, and speleothem hydrochemistry might also reflect 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 of increased storm activity in the Mediterranean Basin between 4.4 and 4.0 ka cal 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 $\delta^{18}O$ values (Fig. 3d) and corresponding ice-rafted debris signals (Fig. 3c), 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 ka cal 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 5000 years in the Western Mediterranean (pale blue bars in Fig. 3). Therefore, the Sidi Ali record shows no dry event and no out-of-phase climatic anomaly but increased humidity at 4.2 ka cal BP simultaneous with North Atlantic cooling.

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

4.4.1 Forcing mechanisms of Early Holocene Bond events and winter rain minima

During the Early Holocene millennial-scale Sidi Ali winter rain minima are parallel to North Atlantic Bond events 8 to 4 (orange bars in Fig. 3). Sidi Ali winter rain minima correspond to 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 and 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 to prominent freshwater outbursts from the Laurentide ice sheet at 9.3 and 8.2 ka cal BP (Alley and Ágústsdóttir, 2005; Fleitmann et al., 2008), indicating evidence of 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 1000 years in North Atlantic temperature changes and Western Mediterranean humidity is a widespread phenomenon in other palaeoclimatic records (Zhao et al., 2010; Cléroux et al., 2012; Fletcher et al., 2013, Ramos-Romána et al., 2018), providing coherence with the eddy frequency band of total solar irradiance (Steinhilber et al., 2009).

4.4.2 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, b) provide evidence of spatio-temporal coherency in the European precipitation pattern. Here, negative NAO indices correspond to 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 1000 years occurred during the Little Ice Age. The Sidi Ali δ^{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 an NAO reconstruction over the past 5200 years. Here, low NAO stages of the filtered Olsen record around 4.2, 3.3, 2.7 and 2.1 ka cal BP and during the Little Ice Age correspond to 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 the 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 to current NAO pattern: the International Ice Patrol's counts of icebergs crossing 48° N in a 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 to 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 palaeoclimatic records from the North Atlantic realm indicates that multi-centennial ice-rafted debris events correspond to cooling phases in the entire region. This is not in accordance with the typical negative-NAO temperature pattern that shows subregional 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 palaeoceanographic evidence of large-scale synchronous Holocene cooling events in the subpolar North Atlantic was recently verified by modelling results (Liu et al., 2017): a reduction in the AMOC corresponds to 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 δ^{18}O winter rain maxima and ice-rafted debris events does not show a 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 to 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 δ^{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.

4.4.3 Middle Holocene hydro-climatic shift in the Western Mediterranean region

Overall, the noticeable match between the Sidi Ali δ^{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 ka cal 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 consistent oceanic–atmospheric interactions between the subpolar North Atlantic and western Europe for the entire Holocene with reference to Bond's ice-rafted debris record. 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 of a large-scale hydro-climatic shift in the North Atlantic–Western Mediterranean region during the Middle Holocene. This Middle Holocene shift in Western Mediterranean hydro-climate is visible in significant frequency changes in humidity at multi-centennial timescales but also at an orbital scale. There is evidence of Early Holocene humidity and Late Holocene aridity in Mediterranean Morocco (Ibouhouten et al., 2010; Limondin-Lozouet et al., 2013), in the central Mediterranean domains of northern 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 to the African Humid Period in the northern 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 Middle Holocene southward shift of the Intertropical Convergence Zone (ITCZ) corresponds to 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, which provides enhanced effective rainfall under negative NAO indices. Previous palaeolimnological and palaeoclimatological studies indicate that the Middle Atlas represents a key region for Holocene hydro-climatic variability in the Western Mediterranean.

In this study, we present an improved Holocene $\delta^{18}O$ 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 $\delta^{18}O$ record with a *Cedrus* record from the same core (Campbell et al., 2017) shows enhanced winter precipitation (low $\delta^{18}O$) and enhanced summer heat (low *Cedrus* pollen concentrations) at an orbital scale 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). At a millennial scale the Sidi Ali $\delta^{18}O$ and the *Cedrus* records are in-phase at 10.2, 8.2 and 6.0 ka cal BP, but there are also indications of 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 (subtropical high) and winter rain (North Atlantic winter cyclones).

Centennial- to millennial-scale peaks in the Sidi Ali $\delta^{18}O$ record represent intervals of Western Mediterranean winter rain minima. The comparison of the Sidi Ali $\delta^{18}O$ 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 and North Atlantic cooling are parallel to arid conditions in the Western Mediterranean (Fig. 4), whereas during the last 5000 years Bond events correspond to wet hydro-climates (Fig. 4). In the Early Holocene, at least two Bond events at 9.3 and 8.2 ka cal BP coincide with prominent freshwater outbursts from the Laurentide ice sheet.

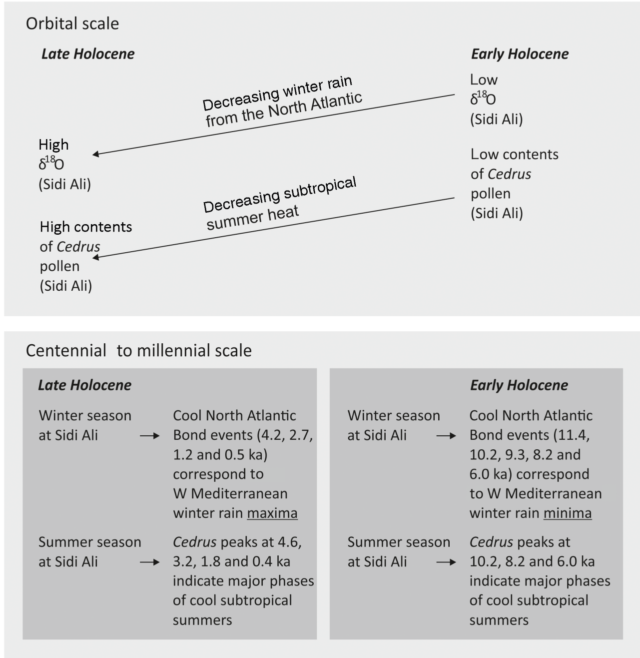

Figure 4. Holocene Lake Sidi Ali record: major conclusions of this study.

Centennial-scale hydro-climatic anomalies show similarities with NAO pattern during the Late Holocene. However, our Sidi Ali $\delta^{18}O$ 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 5000 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 ka cal BP. This is overall in-phase with centennial-scale climatic shifts from cool and wet towards warm and dry hydro-climates during the last 5000 years in the Western Mediterranean.

Data availability. The Sidi Ali stable isotope dataset is available online at https://doi.org/10.13140/RG.2.2.27630.25920 (Zielhofer et al., 2019).

Supplement. The supplement related to this article is available online at: https://doi.org/10.5194/cp-15-463-2019-supplement.

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