Geophysical Research Letters

RESEARCH LETTER
10.1029/2019GL084879

Key Points:
- Holocene rainfall variability in NW Africa is inferred from precisely dated and high-resolution speleothem $\delta^{18}O$ records
- The West African summer monsoon expanded to 31°N in NW Africa during the mid-Holocene
- The African Humid Period ended with an abrupt interval of megadrought around 4 Kyr BP in NW Africa

Supporting Information:
- Supporting Information S1

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Citation:
Sha, L., Ait Brahim, Y., Wassenburg, J. A., Yin, J., Peros, M., Cruz, F. W., et al. (2019). How far north did the African Monsoon fringe expand during the African Humid Period? Insights from Southwest Moroccan speleothems. *Geophysical Research Letters*, *46*, 14,093–14,102. https://doi.org/10.1029/2019GL084879

Received 6 AUG 2019
Accepted 14 NOV 2019
Accepted article online 3 DEC 2019
Published online 13 DEC 2019

How Far North Did the African Monsoon Fringe Expand During the African Humid Period? Insights From Southwest Moroccan Speleothems

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Abstract We present new high-resolution oxygen isotope ($\delta^{18}O$) records from three NW African speleothems located at ~31°N. The present-day rainfall patterns at 31°N in NW Africa are linked to negative winter North Atlantic Oscillation phases. However, on multimillennial time scales, our $\delta^{18}O$ records, together with other hydroclimate records, provide new evidence of humid conditions during the mid-Holocene, a period that was presumably characterized by arid climate. Thus, the apparent increase in moisture during the mid-Holocene is interpreted better as an increase in summer rainfall. This is most likely linked to the expansion of the West African summer monsoon fringe during the African Humid Period, which terminated in our record abruptly around 4 Kyr BP. The temporospatial difference with speleothem records from N Morocco suggests that the High-Atlas Mountains might have been a topographic barrier to further expansion of the West African summer monsoon fringe into higher latitudes.

Plain Language Summary The Holocene African Humid Period in North Africa, characterized by the expansion of vegetation into the Green Sahara, has been linked to the intensification of the West African summer monsoon (WASM). However, the temporospatial pattern of the African Humid Period, especially the northernmost expansion of the WASM, remain a matter of controversy, largely owing to the lack of precisely dated and high-resolution paleoclimatic records. This study presents new high-resolution paleoclimate data based on speleothem oxygen isotope records from a key site at ~31°N in NW Africa. Our data suggest that the WASM expanded to 31°N in NW Africa during the mid-Holocene and terminated abruptly at 4 Kyr BP.

1. Introduction

Climate variability in North Africa has been an important paleoclimate question involving African monsoon variability and vegetation-hydroclimate feedbacks and so forth (e.g., Harrison et al., 2014; Lézine et al., 2011). A large array of paleoclimatic records revealed that North Africa had experienced a remarkable humid period during the mid-Holocene (viz., the African humid period [AHP]) (e.g., Costa et al., 2014; deMenocal et al., 2000; Drake et al., 2011; Gasse, 2000; Lézine et al., 2011; McGee et al., 2013; Shanahan et al., 2015; Skonieczny et al., 2015, 2019; Tierney et al., 2011). The timing and magnitude of the rainfall changes related to the AHP were described by various historical and natural hydroclimate archives, mostly focused on the African monsoon evolution and vegetation hydroclimate feedbacks (Lézine et al., 2011). One of the most dramatic changes observed in North African lake sediment records is the increase of summer precipitation during the AHP, leading to a large expansion of North African lakes, wetlands, grasslands, and shrub lands (e.g., Francus et al., 2013; Holmes, 2008; Shanahan et al., 2015), giving origin to the so-called Green Sahara in the current arid Sahara Desert (deMenocal et al., 2000). However, details of spatial and temporal variations of the North African summer monsoon during the Holocene, especially the temporospatial

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pattern of the AHP and the northernmost expansion of the West African summer monsoon (WASM), still need to be further explored.

Previous studies based on a compilation of available proxy records show that the onset and termination of the AHP varied considerably in both space and time (e.g., deMenocal, 2015; deMenocal & Tierney, 2012; Shanahan et al., 2015). It has been shown that the termination of the AHP might be a time-transgressive event along different latitudes. For example, North African lake records at 6.5°N documented the end of humid conditions around 3 Kyr BP, significantly later than at 20°N, where humid conditions ended around 5 Kyr BP (e.g., deMenocal et al., 2000; McGee et al., 2013; Tierney & deMenocal, 2013). However, discrepancies between marine and terrestrial archives still exist. For example, some marine records off-shore NW Africa (e.g., deMenocal et al., 2000; Tierney et al., 2017) suggest that the AHP termination occurred abruptly, within a matter of centuries, whereas several terrestrial records (e.g., Cockerton et al., 2014; Krpelin, Verschuren, & Lzine, 2008; Krpelin, Verschuren, Lzine, Eggermont, et al., 2008) and modeling studies (e.g., Renssen et al., 2003) indicate that the AHP termination occurred gradually across North Africa.

Modern rainfall at 31°N in NW Africa occurs dominantly during the winter season, which is associated with the westerly jet stream that is modulated by the North Atlantic Oscillation (NAO). However, several paleoclimate records demonstrated that the WASM influence might have reached 31°N during the AHP (i.e., during the early to mid-Holocene) (Tierney et al., 2017). North African lake deposits and eolian sediments analyses suggest that permanent paleolakes expanded at least to 28°N during the AHP (Lézine et al., 2011). Furthermore, leaf wax biomarker records in marine sediment cores indicate that the WASM influence might have expanded to 31°N during the AHP and likely ended abruptly (Tierney et al., 2017). Model simulations using either prescribed or interactive vegetation feedbacks suggest that the changes in atmospheric circulation during the AHP were large and strong enough to advance monsoonal moisture up to ~30°N (e.g., Bosmans et al., 2012; Pausata et al., 2016; Renssen et al., 2006). Hence, a central question is whether and, if so, when and how the WASM regime shifted to a winter NAO hydroclimate-dominated regime during the late Holocene at 31°N in NW Africa.

In this study, we present three new high-resolution and precisely dated speleothem records from Wintimdouine cave (30.77°N, 9.49°W, 1,250 m.a.s.l.) in SW Morocco (Ait Brahim et al., 2019), where modern rainfall variability is largely linked to the NAO state (Ait Brahim et al., 2017; Knippertz et al., 2003; López-moreno et al., 2011). In particular, the pattern of modern NAO-precipitation correlation (e.g., Ait Brahim et al., 2019) revealed that the Wintimdouine cave location is just north of the southern boundary of the NAO-influenced area where less (more) winter rainfall is linked to the positive (negative) NAO state. However, the rainfall variability at the site may not have been solely related to NAO-like conditions in the past, due to, for instance, the nonstationary behavior of the NAO resulting from the gradual shifts of the Azores High and Icelandic Low positions (Ait Brahim, Wassenburg, et al., 2019; Deininger et al., 2016; Wassenburg et al., 2016), as well as possible climate regime changes. Our new records, spanning from 11.5 Kyr BP to the present, allow us to reconstruct the Holocene hydroclimate history of NW Africa at the critical latitude of ~31°N, which provides new insights into the timing of the AHP and the northernmost WASM fringe.

2. Materials and Methods

2.1. Samples and Cave Site

Wintimdouine cave (Figure 1) is located at the northwest edge of the African continent. The modern rainy season in Morocco is from October to April of next year with the highest rainfall amounts recorded from December to February (Born et al., 2010; Schilling et al., 2012) (Figure 1). Three stalagmites (supporting information Figure S1), WIN1, WIN2, and WIN3 (WIN samples), are 197, 217, and 285 mm long with diameters ranging from 20, 30, and 20 mm at the top and 60, 60, and 120 mm at the bottom, respectively. The stalagmites were halved along the growth axis and polished on the cutting surface.

2.2. Mineral Composition Analysis

The WIN samples were analyzed for X-ray diffraction using a Shimadzu XRD 7000 to verify their mineral composition at the Frontier Institute of Science and Technology, Xi'an Jiaotong University. The results indicate that all the samples are composed of calcite.

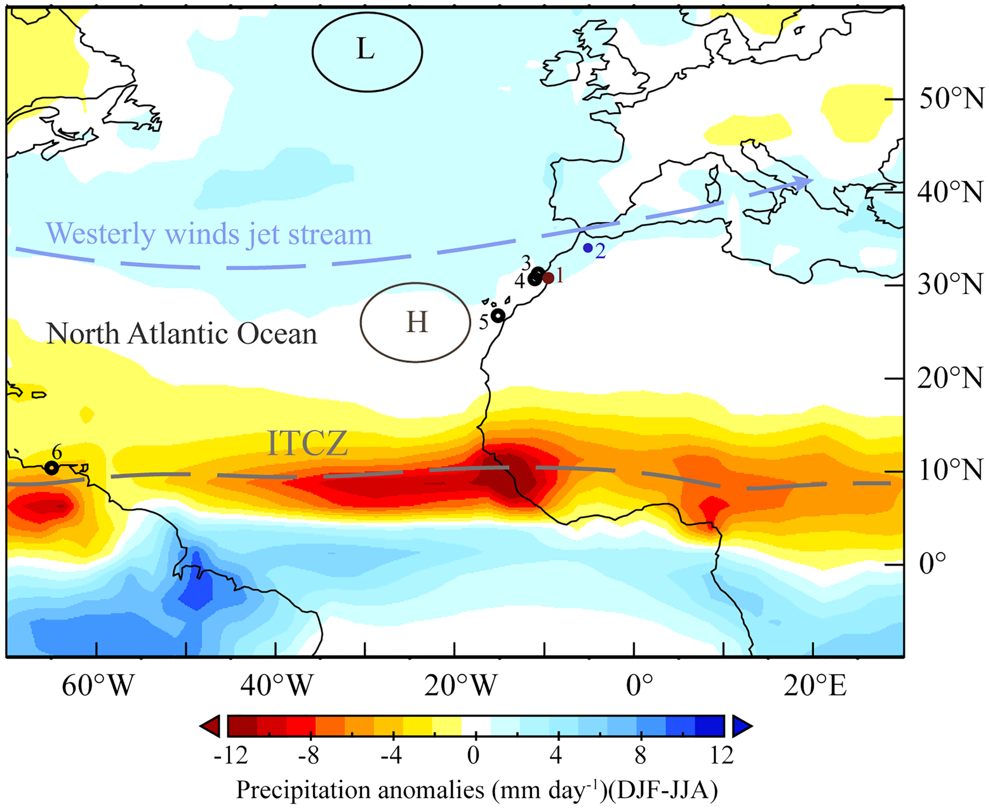

Figure 1. Proxy locations and climatology in NW Africa and surrounding regions. The color-scale shows precipitation amount anomaly between December–February (DJF) and June–August (JJA) in the north Atlantic sector. Mean DJF and JJA precipitation data are from Global Precipitation Climatology Project (Adler et al., 2003) averaged over 1981 to 2010. Locations of the main hydroclimate records discussed in the text are 1 = Wintimdouine cave (this study) and Ifoulki cave (Ait Brahim et al., 2017) (red dot), 2 = Grotte de Piste (Wassenburg et al., 2016) and Chaara cave (Ait Brahim, Wassenburg, et al., 2019) (blue dot), and other proxy sites (black circles) are shown in the map: 3 = OCE437-7-GC27 and 5 = OC437-07-GC37 (Tierney et al., 2017); 4 = GeoB 6007 (Kuhlmann et al., 2004) and GeoB 6007-2 (Holz et al., 2007); and 6 = ODP Site 1002 (Haug et al., 2001). Westerly jet stream (light blue arrow), ITCZ (gray dashed line), and typical positions of the Icelandic Low (IL) (black circle) and the Azores High (AH) (brown circle) are also shown in the map.

2.3. ^{230}Th Dating Method

A total of 3, 27, and 34 ^{230}Th dates was obtained from Samples WIN1, WIN2, and WIN3, respectively, by the ^{230}Th dating technique (Figures S2 and S3 and Tables S1–S6). The ^{230}Th dating was performed at the Isotope Laboratory of the Department of Earth Sciences, University of Minnesota (USA) and the Institute of Global Environmental Change of Xi'an Jiaotong University (China) using a Neptune Plus Multi-Collector Inductively Coupled Plasma Mass Spectrometry. The chemical and instrumental procedures were described in Edwards et al. (1987) and Cheng et al. (2013). All the ages are reported to two standard deviation (2σ) (Tables S1–S6). We made two initial ^{230}Th corrections: (1) our routine correction with an initial $^{230}Th/^{232}Th$ ratio of $4.4 \pm 2.2 \times 10^{-6}$ and (2) the correction with an estimated initial $^{230}Th/^{232}Th$ ratio for the WIN samples ($4.5 \pm 4.5 \times 10^{-6}$) (Text S2). The slight differences between the two corrections in the chronology and uncertainty virtually have no effect on our discussions and conclusions about the multimillennial scale variability of our record which we focused on in this study (Figure S2).

2.4. Calcite Stable Isotope Analysis

For the stable isotope ($\delta^{18}O$) analysis, 1,570 subsamples were milled using a MicroMill from WIN3 along its growth axis at an increment of 0.1 mm. Likewise, 30 and 200 subsamples were obtained from Samples WIN1 and WIN2, respectively. The stable isotope subsamples from WIN1 and WIN2 were drilled along the stalagmites growth axes using a hand drill with a spatial resolution of 1 mm. Isotope-Ratio Mass Spectrometry

(Isoprime 100) was used to measure the stable isotopes in the State Key Lab of Loess and Quaternary Geology, Chinese Academy of Sciences. Results were reported relative to the Vienna Pee Dee Belemnite (VPDB) standard with a long-term reproducibility of 0.1‰ (2σ) or lower.

3. Results

3.1. Age Models

^{230}Th dating results show that WIN1, WIN2, and WIN3 span periods of ~5,520–5,810, ~15–4,360, and ~200–11,530 yr BP, respectively. For each speleothem record, age models were constructed using Constructing Proxy Records from Age (COPRA) (Breitenbach et al., 2012), Oxcal (Ramsey, 2008), and Intra-Site Correlation Age Modeling (ISCAM) (Fohlmeister, 2012) methods, respectively (Figure S3). The age models established by different programs are broadly consistent within uncertainties, and thus, conclusions of this study are not sensitive to different age models (Figure S3). The dating results show that the WIN3 stalagmite has a hiatus between ~1,940 and 3,950 yr BP (64 and 76 mm from the top), whereas the WIN2 stalagmite has a hiatus between ~3,260 and 4,060 yr BP (between 170 and 183 mm from the top). WIN2 and WIN3 δ^{18}O records are in good agreement within uncertainties during their contemporary growth period from ~4,360 to 200 yr BP (Figures S4), providing an important replication test (see the next section).

3.2. Interpretation of the δ^{18}O Records

WIN1, WIN2, and WIN3 δ^{18}O records replicate within uncertainties in the common growth periods on millennial to even multidecadal time scales (Figure S4a). The replications are confirmed by statistically significant correlations between WIN3 and WIN1 ($r = 1$ at the 95% confidence level, calculated using ISCAM) and between WIN3 and WIN2 ($r = 0.58$ at 95% confidence level between ~3.3 and 0 Kyr BP and $r = 1$ at 95% confidence level between age of ~3.3 and 4.0 Kyr BP, calculated using ISCAM), and strongly suggest that their overall δ^{18}O variability is mainly reflecting the δ^{18}O of precipitation ($\delta^{18}O_p$) (e.g., Hendy, 1971; Wang et al., 2001). Moreover, ISCAM was performed to construct a representative composite record (hereafter the WIN record) from WIN1, WIN2, and WIN3 δ^{18}O records by adjusting each record within their dating uncertainties using a Monte-Carlo approach (Figure S4).

The δ^{18}O of meteoric precipitation, reflected by our speleothem δ^{18}O, can be affected by many hydroclimatic factors (e.g., Cheng et al., 2019; Lachniet, 2009). Stable isotope analyses of meteoric water and groundwater collected from Wintimdouine cave site and the city of Agadir (~36 km away from Wintimdouine cave) between October 2014 and October 2015 show that the correlation between temperature and δ^{18}O of precipitation is insignificant. Instead, the "amount effect" or an inverse correlation between rainfall amount and δ^{18}O has been shown to be significant in this region (Ait Brahim et al., 2016, 2017). A previous study of a stalagmite δ^{18}O record over the last millennium from Ifoulki (IFK) cave near Wintimdouine cave (~4 km away) (Figure 1) demonstrated that the speleothem δ^{18}O is a proxy of rainfall amount (Ait Brahim et al., 2017). As such, we only focus on the interpretation of Wintimdouine cave δ^{18}O records, which indicate changes in regional precipitation δ^{18}O, consistent with the interpretation of the Ifoulki cave δ^{18}O records ($r = 0.47$ at 95% confidence level for IFK1 and WIN records, calculated using ISCAM) (Figure S5) and instrumental data. In addition, we are aware that large δ^{18}O excursions might reflect changes of moisture sources and/or the climate regime, which we take into considering in the following sections.

4. Discussion

4.1. Temporospatial Patterns of Climate at ~31°N in NW Africa

The δ^{18}O values in the WIN record show a multimillennial "heavy-light-heavy" pattern across the Holocene (Figure 2a). Our data reveal heavy δ^{18}O values during the early Holocene, with two abrupt short intervals of light δ^{18}O values around 10.5 and 9.8 Kyr BP, coherent with the start of wet conditions in NW Africa around 10 Kyr BP, as seen elsewhere in northern Africa (e.g., Shanahan et al., 2015; Skonieczny et al., 2015). Afterward, the lighter δ^{18}O values became persistent throughout the mid-Holocene (between 9 and 4 Kyr BP), coincident with the timing of the AHP and possibly reflecting overall humid conditions, followed by heavier δ^{18}O values during the late Holocene. The WIN record has a growth hiatus between ~4 and 3.3 Kyr BP. The hiatus replicates in both WIN2 and WIN3 stalagmites, and the δ^{18}O values show an abrupt change before and after this period as well (Figure 2a). This replicated hiatus might imply a megadrought

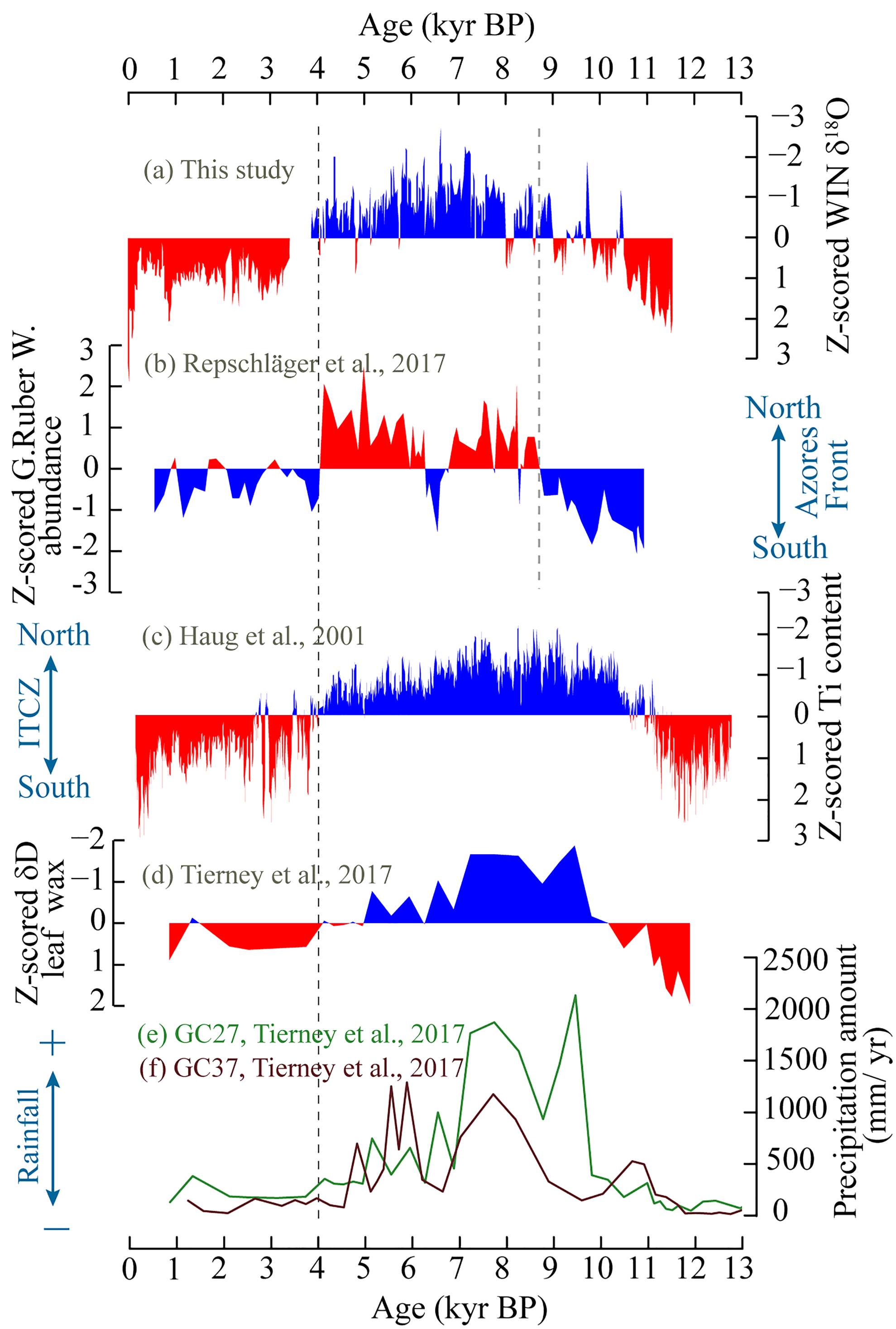

Figure 2. Comparison of the WIN record with other hydroclimate records: from top to bottom, (a) The *z*-scored WIN $\delta^{18}O$ record (30.77°N, 9.49°W) (this study). (b) Position of the Azores Front based on the abundance of the planktonic foraminifera Globigerinoides ruber (G. ruber W.) in the sediment core in the vicinity of the Azores. The high value corresponds to a more northward shift of the Azores Front (Repschläger et al., 2017). (c) The z-scored bulk Ti content of Cariaco Basin sediments from ODP site 1002 (10.71°N, 65.17°W). The low value corresponds to high precipitation amount associated with a more northward mean latitude of the ITCZ (Haug et al., 2001). (d) The *z*-scored leaf wax δD record from marine sediment core OCE437-7-GC27 (30.88°N, 10.63°W) (Tierney et al., 2017). (e and f) Quantitative reconstruction of western Saharan precipitation from leaf wax δD records in the marine sediment core of OCE437-7-GC27 (30.88°N, 10.63°W) (dark green) and OCE437-7-GC37 (26.82°N, 15.12°W) (brown) (Tierney et al., 2017). The *y* axes are inverted to show drier conditions downward. The gray dash line (short) depicts the starting time of positive winter North Atlantic Oscillation (NAO+)-like state. The black dash line (long) depicts the termination of the AHP which coincided with an interval of megadrought around 4 Kyr BP in NW Africa.

interval (~4 to 3.3 Kyr BP), presumably in line with the general concept of abrupt climate shifts in Western Sahara at the end of the AHP (e.g., deMenocal et al., 2000), which might be accompanied by a shift of climate regimes and thus moisture sources in North Africa.

Broadly, marine records from the same latitude as Wintimdouine cave (~31°N) show a multimillennial "dry-wet-dry pattern" across the Holocene (Holz et al., 2007; Tierney et al., 2017), consistent with the "heavy-light-heavy" $\delta^{18}O$ pattern in the WIN record. In particular, a record of terrigenous supply offshore Morocco located at ~31°N (GeoB 6007-2) (Holz et al., 2007) revealed generally humid climate conditions in northern Africa between ~9 and 4 Kyr BP, suggestive of increased continental runoff during the period. Another record based on leaf wax δD from a marine sediment core located at 31°N (Tierney et al., 2017) (Figure 2d) shows enhanced precipitation as well during the mid-Holocene between ~10 and 5 Kyr BP, suggesting a consolidated vegetation cover and thus an increase of continental rainfall, which supports the hypothesis of northern shift of the WASM and related humid conditions in NW Africa during the AHP (Tierney et al., 2017) (Figures 2e and 2f).

Recently, a gradual northward shift in the position of the Azores Front during the mid-Holocene was proposed (Repschläger et al., 2017). This pattern is similar to a positive winter NAO-like state from ~8.7 to 4 Kyr BP (Figure 2b). Hence, the lighter $\delta^{18}O_p$ and inferred increase of rainfall at the Wintimdouine site during this period cannot be attributed to negative NAO-like states. Instead, the northward shift of the WASM might have played an important role in modulating the hydroclimate during the mid-Holocene at 31°N as also suggested by other studies (e.g., Tierney et al., 2017). Hence, in accordance with paleorecords from 31°N, our results suggest that the northernmost expansion of the WASM reached 31°N in NW Africa between 9 and 4 Kyr BP (Figure 2a). This pattern of prevalent humid climate conditions coincides broadly with episodes of high water level in African lakes (e.g., Dupont, 2011; Gasse, 2000), such as wetter conditions than today from ~10 to 5–4 Kyr BP (Gasse, 2002).

4.2. Potential Mechanisms Behind the Northward Expansion of the WASM During the AHP

Previous studies have shown that besides the dominant factor of Northern Hemisphere summer insolation (e.g., Kutzbach, 1981), vegetation and dust feedbacks are important as well for understanding past and present monsoons (e.g., Gaetani et al., 2017; Pausata et al., 2016). A large reduction in tropospheric dust during the mid-Holocene over North Africa would have enhanced the Saharan heat low, thus drawing the NW African monsoon further northward (Gaetani et al., 2017; Pausata et al., 2016). For example, model results by Pausata et al. (2016) suggest that the monsoon reached ~31°N, when the model was forced with both prescribed vegetation and reduced dust concentrations. However, other GCM simulations suggest limited enhancement of precipitation due to reduced dust during the mid-Holocene, while other factors such as land surface conditions and atmospheric convection responses should also be taken into consideration (Hopcroft & Valdes, 2019).

Furthermore, the northward shift of the ITCZ has been widely proposed as an amplifier of humid conditions in Africa during the AHP (e.g., Forman et al., 2014; Nicholson, 2009; Tierney et al., 2008; Timm et al., 2010). Indeed, the energetic constraints on the ITCZ position have several implications, also for the African monsoon. During the Holocene thermal maximum (Haug et al., 2001), the summertime warming of the northern extratropics led to further northward seasonal excursion of the ITCZ (Schneider et al., 2014), likely resulting in a further expansion of the area influenced by the WASM over northern Africa. A comparison of our data with a record reflecting northward/southward shifts of the ITCZ (Figure 2c) (inferred from the Cariaco Basin Ti record from ODP Site 1002; Haug et al., 2001) reveals a remarkable transition of the hydrological cycle over northern Africa during the AHP, probably related to the northward migration of the ITCZ, and/or further expansion of the WASM (Schneider et al., 2014; Skonieczny et al., 2015). The Holocene evolution of precipitation in NW Africa at 31°N could thus be explained as follows:

From 11.5 to 9 Kyr BP, the WASM fringe did not reach 31°N yet, as shown by the relatively heavy $\delta^{18}O$ values similar to (or slightly heavier than) modern values in the WIN record (Figure 2), whereas there is evidence that the ITCZ had already started shifting northward during this period (e.g., Skonieczny et al., 2015).

Between 9 and 4 Kyr BP, the climate signal from the WIN record is synchronous to the persistent northward position of the ITCZ (Figure 2c), which likely triggered or amplified the expansion of the WASM further northward during the AHP. Interestingly, synchronous growth hiatuses in two WIN2 and WIN3 records

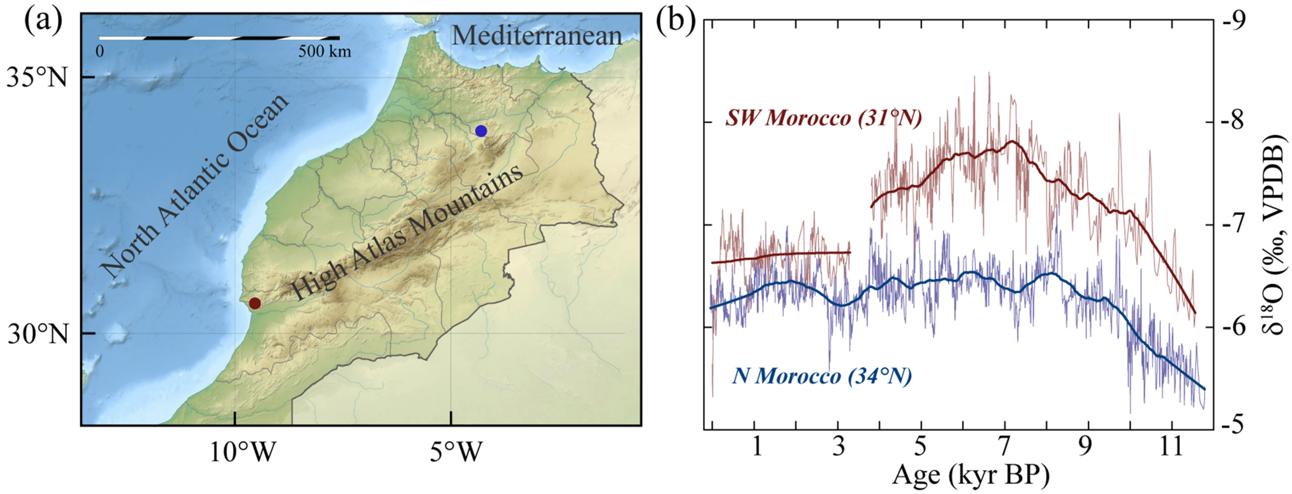

Figure 3. Speleothem records reflecting different climate patterns between N and SW Morocco during the Holocene. (a) The locations of Wintimdouine cave (30.77°N, 9.49°W, 1,250 m.a.s.l.) (red dot, this study) and Chaara cave (33.96°N, 4.25°W, 1,260 m.a.s.l.) (blue dot) [Ait Brahim et al., 2019a] (source: https://www.mapsland.com). (b) Comparison of composite $\delta^{18}O$ records from Chaara cave (blue line) [Ait Brahim et al., 2019a] from N Morocco and Wintimdouine cave (red, this study) from SW Morocco. The N Moroccan speleothem records consist of aragonite which is associated with larger oxygen isotope fractionation during formation as compared to calcite (0.8‰) (Fohlmeister et al., 2018). In order to compare the absolute $\delta^{18}O$ values, the N Moroccan aragonite $\delta^{18}O$ was corrected to the equivalent calcite $\delta^{18}O$ values by subtracting 0.8‰. The bold curves show the 2,000-year moving average of each time series. The light colored curves indicate the original data set.

suggest a period of drought initiating around 4 Kyr BP (Figure 2a), coincident with the timing of several abrupt climate change events identified in many Holocene records around the world (e.g., Bond et al., 2001; Li et al., 2018; Marchant & Hooghiemstra, 2004; Mayewski et al., 2004; Roland et al., 2014). This abrupt climate event has indeed been linked to collapse of ancient civilizations in Northern Hemisphere subtropical regions, including Mesopotamia, Egypt, and the Indus Civilization [e.g., Staubwasser & Weiss, 2006; Weiss, 2016]. This phase occurred in the context of a weakening trend in Northern Hemisphere summer insolation and coincides with a southward shift of the ITCZ, which was also suggested to play an important role in the aridification of Northern Hemisphere tropics and the termination of the AHP (Mayewski et al., 2004).

During the late Holocene, both fully coupled climate model simulations and geological data suggest that the decreasing rainfall amount resulted from a decrease in boreal summer insolation, which caused a southward retreat of the summer monsoonal rains (e.g., Bradtmiller et al., 2016), whereas the ITCZ shifted southward (Toggweiler, 2009). Meanwhile, the strength and location of the Icelandic Low and/or Azores High could gradually shift northeastward and southwestward, respectively, resulting in modern NAO patterns. Interestingly, after 3.3 Kyr BP, our speleothem $\delta^{18}O$ values are consistently heavier than the mid-Holocene, suggesting a change in the climate regime and/or the moisture source of precipitation at the Wintimdouine site (Figure 2a). Hence, the mean state of the late Holocene climate in SW Morocco might be similar to the modern hydro-climate patterns, which are modulated largely by the NAO.

4.3. The WASM Belt Did Not Reach ~34°N During the AHP

The primary processes affecting the modern $\delta^{18}O$ variability (e.g., rainfall amount, temperature, moisture source and trajectories, etc.) were believed to be similar in both N and SW Morocco. However, in contrast to the aforementioned monsoonal signal in SW Moroccan speleothems during the mid-Holocene, a completely different climate pattern was observed in speleothem records from N Morocco (Figure 3). Based on speleothem $\delta^{18}O$ records from N Morocco (~34°N) and a compilation of climate records, there is evidence that positive NAO-like conditions prevailed during the mid-Holocene, whereas the early Holocene was characterized by relatively negative NAO-like conditions on multimillennial time scales (Ait Brahim, Wassenburg, et al., 2019). However, our data show that the speleothem $\delta^{18}O$ values dropped to values as low as −8.5‰ in SW Morocco, which together with other hydroclimate records, suggest enhanced rainfall amount in SW Morocco during the AHP. Moreover, N Moroccan speleothem $\delta^{18}O$ records are characterized by a smaller amplitude (~1‰) than our SW Moroccan record (~2‰) during the mid-Holocene (Figure 3b). These observations can be explained by the northward expansion of the WASM during the AHP, which could reach the Wintimdouine site, but not the N Moroccan cave sites at ~34°N. This might be related to the weakening of the WASM at higher latitudes and the local topography of Morocco as well. Indeed, the High Atlas Mountains might have created a topographic barrier (Ait Brahim et al., 2016) blocking the WASM-related moisture flow toward N Morocco (Figure 3a).

5. Conclusions

In this study, we present high-resolution, absolute-dated $\delta^{18}O$ records of stalagmites from Wintimdouine cave in SW Morocco at ~31°N. On multimillennial time scales, our data reveal a transition from dry to humid conditions during the early Holocene (~9 Kyr BP) and a resumption of drier conditions during the late Holocene at ~4 Kyr BP. The present-day rainfall patterns at the Wintimdouine cave area are largely modulated by the NAO pattern. Although the mid-Holocene is characterized by a positive NAO-like state on multimillennial time scales, wetter conditions are recorded in our speleothem and other hydroclimate records. This mid-Holocene humid conditions might be explained by the large spatial expansion of the WASM, resulting from the high Northern Hemisphere summer insolation and northward-shifted ITCZ during the AHP. Hence, we provide proxy evidence for a northernmost expansion of the WASM that likely reached ~31°N during the mid-Holocene. In addition, our data suggest that the termination of the AHP occurred abruptly with a drought interval initiating around 4 Kyr BP in NW Africa. This timing coincides with a southward shift of the ITCZ that has been linked to well-known abrupt climate change in Northern Hemisphere. Moreover, different hydroclimate pattern in speleothem $\delta^{18}O$ records from N Morocco reveals that the humid conditions did not reach ~34°N during the AHP. The High Atlas Mountains likely acted as a topographic barrier blocking the WASM-related moisture flow from reaching farther into higher latitudes.

Data Availability Statement

The data presented in this paper are available online on the NOAA paleoclimate database (https://www.ncdc.noaa.gov/paleo/study/28333).

Acknowledgments
This work was supported by grants from NSFC (41888101, 41472140, 41731174, and 41561144003), U.S. NSF Grant 1702816, and the Postdoctoral Science Foundation of China (Grant 2018M640971) to Yassine Ait Brahim.

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