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Moisture and Seasonality Shifts Recorded in Holocene and Pleistocene Speleothems From Southeastern Arabia

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Key Points:

- Hydrogen and oxygen isotopes in fluid inclusions in stalagmites from Hoti Cave, Northern Oman, reveal changes in the source of rainfall
- Rainfall during the early and middle Holocene originated from the Indian Ocean and was associated with the Indian summer monsoon
- A change in the seasonality and reduction in rainfall at ~6,300 years before present had a profound impact on communities in Northern Oman

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

The source and seasonality of rainfall in southern Arabia during the early- to mid-Holocene and preceding humid periods are controversial because fossil lacustrine sediments provide solely indirect information on the amount of rainfall. Hydrogen and oxygen isotope measurements on fluid inclusion water trapped in Holocene and Pleistocene stalagmites from Hoti Cave in Northern Oman are direct indicators of the isotopic composition of paleoprecipitation. Isotope values of fluid inclusions formed during peak interglacial periods plot along monsoonal water lines and are indicative of a southern monsoonal moisture source. The last monsoon-dominated period lasting from ~10,100 to 6,300 years before present was terminated within a few decades in southeastern Arabia. The subsequent reduction in rainfall amount and change from predominantly summer to predominantly winter rainfall had a profound impact on human communities living in this area and triggered migration from inland to coastal areas where resources were more abundant.

Plain Language Summary

During the Quaternary period, the Arabian Peninsula experienced short intervals of enhanced rainfall, turning the Arabian Desert into a savannah-type landscape with abundant lakes and wetlands. These intervals are well-documented in lake sediments and cave deposits throughout Arabia, whereas the source of rainfall is uncertain. Ancient rainwater trapped in fluid inclusions in stalagmites from Hoti Cave, Northern Oman, allows us to determine moisture source changes over the last 350,000 years before present. Using new analytical methods to extract the water from fluid inclusions and measure its hydrogen and oxygen isotopic composition, we are able to show that greatly enhanced rainfall was caused by an intensification and greater northward extension of the African and Indian monsoons into Arabia. For the last humid period between ~10,500 and 6,300 years before present, stalagmites from Hoti Cave reveal an abrupt termination of the monsoon-dominated period, a sharp decline in precipitation and change from a summer- to winter-dominated rainfall regime in southeastern Arabia. As a result, human communities were severely affected by this major climatic change and forced to migrate from inland to coastal areas, where water and resources were more abundant.

1. Introduction

Paleoclimate reconstructions from the Arabian Peninsula helped to improve our knowledge of the timing, duration, and spatial extent of pluvial periods affecting the Arabian Peninsula. In southern Arabia, for instance, speleothem records from caves in Oman and Yemen reveal the occurrence of at least 21 pluvial periods over the last ~1.1 million years (Burns et al., 1998, 2001; Fleitmann et al., 2011; Nicholson et al., 2020). These pluvials coincided with peak interglacial periods when the African and Indian summer monsoons were intensified and had a greater northward extent than today. The last humid period between ~10,500 and 6,300 years BP transformed most of Arabia into a savannah-type landscape with abundant lakes and wetlands (e.g., Rosenberg et al., 2011). The duration of this wetter period appears to be diachronous across the Arabian Peninsula, most likely owing to both meridional and zonal displacements of the Intertropical Convergence Zone (ITCZ) and associated changes in the range of the African and Indian monsoons (Fleitmann, Burns, Mudelsee, et al., 2003; Fleitmann et al., 2007; Lézine et al., 2017; Preston et al., 2015) (Figure 1).

Though the general Holocene moisture evolution is well-known, uncertainties exist regarding the sources, seasonality, and amount of rainfall across the Arabian Peninsula (Engel et al., 2017; Enzel et al., 2015; Kutzbach et al., 2014; Staubwasser & Weiss, 2006). Several hypotheses exist as enhanced rainfall could have originated

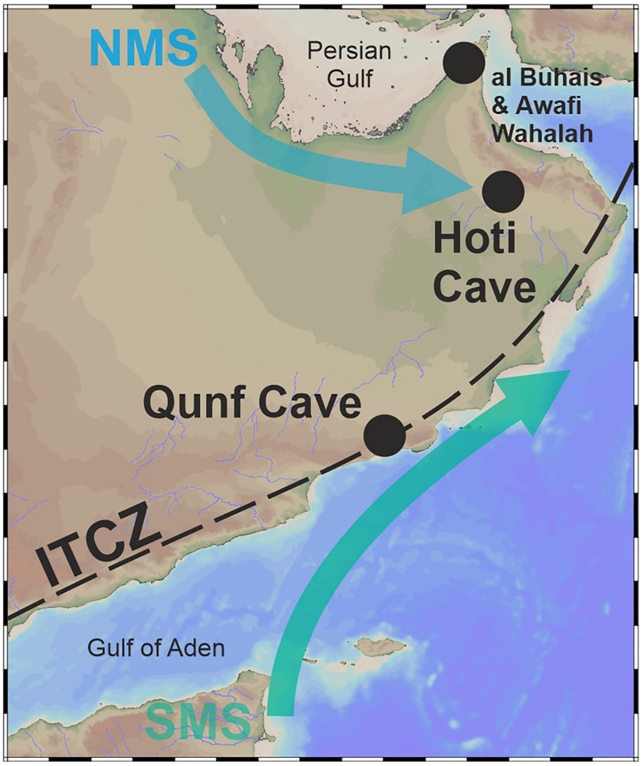

Figure 1. Map showing the location of Hoti and Qunf Caves and climate records from Awafi (Parker et al., 2004, 2006) and Wahalah (Preston et al., 2015). Also shown is the location of the archeological site al-Buhais (Kutterer & Uerpmann, 2009). Arrows mark the northern and southern moisture sources. The black-dashed line denotes the present-day location of the summer Intertropical Convergence Zone.

from several different sources due to the complex interplay between continental and maritime air masses, distribution of water bodies (Mediterranean, Red Sea, Arabian Sea, and Persian Gulf) and complex topography. In southern Arabia, several potential moisture sources were proposed for the Holocene humid period: (a) a southern moisture source (SMS; Indian Ocean), (b) a northern moisture source (NMS; Mediterranean), (c) eastern moisture source (Persian Gulf), or (d) the combination of several moisture sources (e.g., NMS and SMS). Rainfall from a SMS is either associated with the African and Indian summer monsoons or with more frequent tropical cyclones with moisture influx from the Indian Ocean and Arabian Sea (e.g., Burns et al., 2001; Fleitmann, Burns, Mudelsee, et al., 2003; Fleitmann, Burns, Neff, et al., 2003; Nicholson et al., 2020). Alternatively, higher rainfall could have also originated from a NMS as winter-spring precipitation increased due to an intensification of the mid-latitude westerlies during the early and mid-Holocene (Arz et al., 2003; Enzel et al., 2015). In addition, a stronger northeast monsoon and enhanced advection of moisture from the Persian Gulf toward northern Oman has been proposed as a source for enhanced rainfall (Enzel et al., 2015).

Current uncertainties regarding past moisture sources in Arabia are related to the limitations of lacustrine and speleothem paleoclimate records to provide direct information on the source or seasonality of precipitation. For instance, speleothem-based oxygen isotope calcite records ($\delta^{18}O_{ca}$) are influenced by multiple and often competing processes (Lachniet, 2009). Other climate proxies such as lacustrine sediments, dunes and pollen allow to differentiate between wetter and drier climatic intervals, but do not contain information on source or seasonality of rainfall. A way to overcome the current limitations and uncertainties of lacustrine and speleothem $\delta^{18}O_{ca}$ records is to measure hydrogen ($\delta^{2}H_{fi}$) and oxygen ($\delta^{18}O_{fi}$) isotopes of microliter amounts of fluid inclusion water extracted from speleothems. Fluid inclusions are abundant in speleothems (0.5%–2%) and natural repositories of drip water and rainfall (Fleitmann, Burns, Mudelsee, et al., 2003). New analytical methods and Wavelength Scanned Cavity Ringdown Spectroscopy (WS-CRDS) allows simultaneous and precise measurements of $\delta^{2}H_{fi}$ and $\delta^{18}O_{fi}$ on microliter amounts of fluid inclusion water (Affolter et al., 2014; Arienzo et al., 2013), thereby providing direct estimates for the isotopic composition of rainfall at the time when the speleothem was growing. When combined with isotope studies on modern rainfall, $\delta^{2}H_{fi}$ and $\delta^{18}O_{fi}$ data permit to reconstruct moisture fluxes, the origin, amount, and seasonality of rainfall in southern Arabia. Here, we present new isotope measurements of speleothem fluid inclusion water on Pleistocene and Holocene stalagmites from Hoti Cave in Northern Oman. This area is ideal to investigate the interplay between the mid-latitudinal westerlies and monsoons and to identify moisture source changes related to changes in the latitudinal position of the monsoonal rainfall belt. The new Hoti Cave paleorainfall reconstruction helps to establish more plausible causal links between climatic and cultural changes, as knowledge of the source and seasonality of rainfall is crucial for climate-human relationships in southern Arabia.

2. Cave Setting

Hoti Cave (23°05'N; 57°21'E, 800 m above sea level) is situated on the southern side of the Jabal Akhdar (Figure 1). The ~5 km-long cave is a subterranean wadi with two entrances. In Northern Oman, Mediterranean frontal systems are the main source of rainfall, which are most frequent between January and March. Additional minor sources are local convective storms during summer and tropical cyclones that reach Northern Oman once every 5–10 years (Weyhenmeyer et al., 2000, 2002). Annual rainfall is low and ranges from ~55 to 255 mm yr^{-1} in the vicinity of Hoti Cave (station AI Hamra, 1974–1997). Cave air temperature is around 25–27°C and relative humidity varies between 60% and 100%.

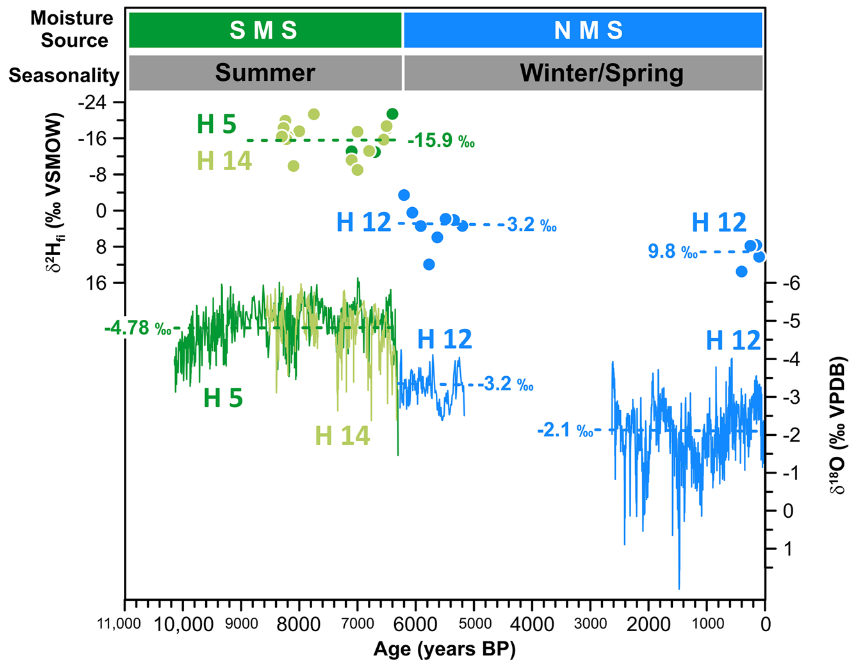

Figure 2. The δD_{fi} and $\delta^{18}O_{ca}$ records for stalagmites H5, H14, and H12. Note, stalagmite H14 $\delta^{18}O_{ca}$ values were shifted by −0.5‰ to account for a systematic isotopic offset to stalagmite H5. Dashed lines mark average δD_{fi} and $\delta^{18}O_{ca}$ values for each record.

3. Materials and Methods

Speleothems were collected from Hoti Cave (Figure S1 in Supporting Information S1). Most of the samples grew during the Holocene (stalagmites H5, H12, and H14) and late and middle Pleistocene (stalagmite H13) (Figure S2 in Supporting Information S1). The chronologies of all stalagmites were presented in previous publications (Cheng et al., 2009; Fleitmann et al., 2007; Neff et al., 2001). Unpublished ages for stalagmite H14 are provided in Table S1 in Supporting Information S1.

Isotope measurements were performed on a Finnigan Delta V Advantage Isotope Mass Spectrometer coupled to an automated carbonate preparation system (Gasbench II) or VG Prism II at the Institute of Geological Sciences, University of Bern. The precision (1σ) of both instruments is ≤0.1‰ for $\delta^{18}O$. Isotope values are reported relative to the Vienna Peedee Belemnite standard.

A total of 83 fluid inclusion water isotope measurements were performed on all stalagmites. Samples were obtained from more porous parts of the stalagmites where fluid inclusions were more abundant. Deuterium (δD_{fi}) and oxygen ($\delta^{18}O_{fi}$) isotopes of speleothem fluid inclusion water were analyzed at the Department of Environmental Sciences, University of Basel, using the extraction method developed by Affolter et al. (2014, 2015) (Text S1 and Table S2 in Supporting Information S1). To extract the water calcite blocks of ∼25 × 5 × 5 mm (L, W, and H) were placed into a copper tube and connected to the measuring line, heated to ∼140°C and crushed. The liberated water was then transported to a WS-CRDS system (Picarro L2140-i analyzer) under humid conditions to prevent fractionation and minimize memory effects. On average, ∼1 μl of water was released. Precision is ∼1‰ for δD_{FI} and ∼0.2‰ for $\delta^{18}O_{FI}$. Fluid inclusion values are reported on the Vienna Standard Mean Ocean Water scale (Table S2 in Supporting Information S1).

4. Results and Discussion

4.1. Moisture Sources During Humid Periods in South-Eastern Arabia

The Hoti $\delta^{18}O_{ca}$ record shows a distinct decadal- to multidecadal-scale variability. The most distinct feature is a positive step-like isotopic shift of 2–4‰ at ∼6,300 years BP (Figure 2). This shift is also apparent in the δ^2H_{fi} record and related to a major change in the source and amount of rainfall above the cave. This interpretation is primarily based on the distinctly different isotopic signatures of modern rainfall with northern versus southern sources in Northern Oman.

At present, two moisture sources recharge groundwater in Northern Oman; one associated with winter/spring frontal depression systems moving from the Mediterranean across the Arabian Peninsula and one with occasional (5–10 years) tropical cyclones from the Indian Ocean (Weyhenmeyer et al., 2000, 2002). Rainfall from both sources has distinctly different isotopic signatures, with rainfall from a NMS ranging from −4.5 to +1‰ in $\delta^{18}O$ and from −25 to +5‰ in δ^2H (Figure 3a) (Weyhenmeyer et al., 2000, 2002). In contrast, rainfall from a SMS is generally more negative, with $\delta^{18}O$ ranging from −10 to −2‰ and δ^2H from −75 to −15‰. Therefore, two Local Meteoric Water Lines (LMWL) exist for Northern Oman (Weyhenmeyer et al., 2002), a northern LMWL (N-LMWL; $\delta^2H = 5.0\ \delta^{18}O + 10.7$) and southern LMWL (S-LMWL; $\delta^2H = 7.2\ \delta^{18}O - 1.1$) (Figure 3a). The slope and intercept of the N-LMWL is very similar to the LMWL from Bahrein ($\delta^2H = 5.5\ \delta^{18}O + 6$; Gat et al., 2001), where rainfall is also associated with Mediterranean frontal systems. The S-LMWL, however, is almost identical with the LMWL from New Delhi ($\delta^2H = 7.15\ \delta^{18}O + 2.6$; Pang et al., 2004) where more than 80% of total annual rainfall is contributed by the ISM which is fueled by moisture originating from the Arabian Sea, Indian Ocean, and Bay of Bengal.

Isotope values of Hoti Cave drip water and local groundwater samples plot between both LMWLs and indicate that rainfall from the NMS and SMS contributes to present-day groundwater recharge (Fleitmann, Burns, Neff, et al., 2003; Matter et al., 2006; Weyhenmeyer et al., 2000, 2002) (Figure 3b). Isotope ratios of recent fluid inclusions (<100 years; $n = 3$) in stalagmite H12 exhibit rather positive values of around +8.6‰ for δ^2H_{fi} and +1.3‰ for $\delta^{18}O_{fi}$ (Figure 2), which is consistent with the positive $\delta^{18}O_{ca}$ values of around −2.1‰ (Figure 2). Late Holocene fluid inclusion isotope values plot along the Akhdar Water Line ($\delta^2H = 5.1\ \delta^{18}O + 3$; Macumber et al., 1997) and are slightly more positive than drip water values, possibly due to kinetic effects (evaporation). Furthermore, the values are more enriched compared to any S-LMWL values and the slope of drip and late Holocene fluid inclusion values is parallel with the N-LMWL and not the S-LMWL. Isotope ratios of fluid inclusion water extracted from the mid-Holocene section of stalagmite H12 are only slightly more negative, averaging +3.2‰ in δ^2H_{fi} and +0.5‰ in $\delta^{18}O_{fi}$ (Table S2 in Supporting Information S1). In contrast, isotope ratios of fluid inclusions from the early and mid-Holocene stalagmites H5 and H14 are more depleted, with mean δ^2H_{fi} and $\delta^{18}O_{fi}$ values of around −15.9‰ and −1.7‰, respectively. However, isotope ratios of early to mid-Holocene fluid inclusions are generally more positive compared to those obtained from stalagmite H13 for MIS 5e, MIS 7, and MIS 9 peak interglacial periods (Figure 3c). For instance, MIS 5e δ^2H_{fi} and $\delta^{18}O_{fi}$ values average −38.5‰ and −5.1‰, respectively, within a similar range as isotope ratios of fluid inclusion water trapped during MIS 7 (−30.6‰ and −4.6‰) and MIS 9 (−27.6‰ and −3.7‰).

Isotope values of fluid inclusions trapped during peak interglacial periods corresponding to the early to mid-Holocene, MIS 5e, MIS 7, and MIS 9 plot either very close or right onto the S-LMWL, clearly revealing that the greatest proportion of annual rainfall originated from a SMS (Figure 3c). Some samples show a slightly larger deviation from the S-LMWL, which could be related to slight postdepositional changes of $\delta^{18}O_{fi}$ values due to the interaction between the host calcite and fluid inclusion water (Demény et al., 2021). Because the ISM was stronger during peak interglacial periods (e.g., Fleitmann et al., 2011), enhanced rainfall in Northern Oman was most likely caused by a northward expansion of the monsoonal rain belt and northward displacement of the summer ITCZ. Hoti Cave δ^2H_{fi} and $\delta^{18}O_{fi}$ values indicate that the Arabian Sea and Indian Ocean were the dominant moisture sources in south-eastern Arabia, whereas the contribution of moisture from the Mediterranean was very minor as all fluid inclusion isotope values plot along the S-LMWL (Figure 3c). This observation contradicts assumptions that rainfall associated with mid-latitude westerly systems from the Mediterranean was a significant additional source of rainfall in south-eastern Arabia during the early and mid-Holocene (Enzel et al., 2015; Kutzbach et al., 2014; Staubwasser & Weiss, 2006). Likewise, the Hoti fluid inclusion data reveal that southeastern Arabia was affected by the ISM during the early mid Holocene and previous peak interglacial periods corresponding to MIS 5e, MIS 7, and MIS 9. Thus, the ISM rainfall belt was located north of Hoti Cave and 23°N, respectively, between ~10,100 and ~6,300 years BP.

4.2. Termination of the Holocene Humid Period in South-Eastern Arabia

The marked mid-Holocene positive shift in the stalagmite H5 $\delta^{18}O_{ca}$ record is related to the termination of the humid and monsoon-dominated period in Northern Oman within a few decades (Figure 4). This is supported by a

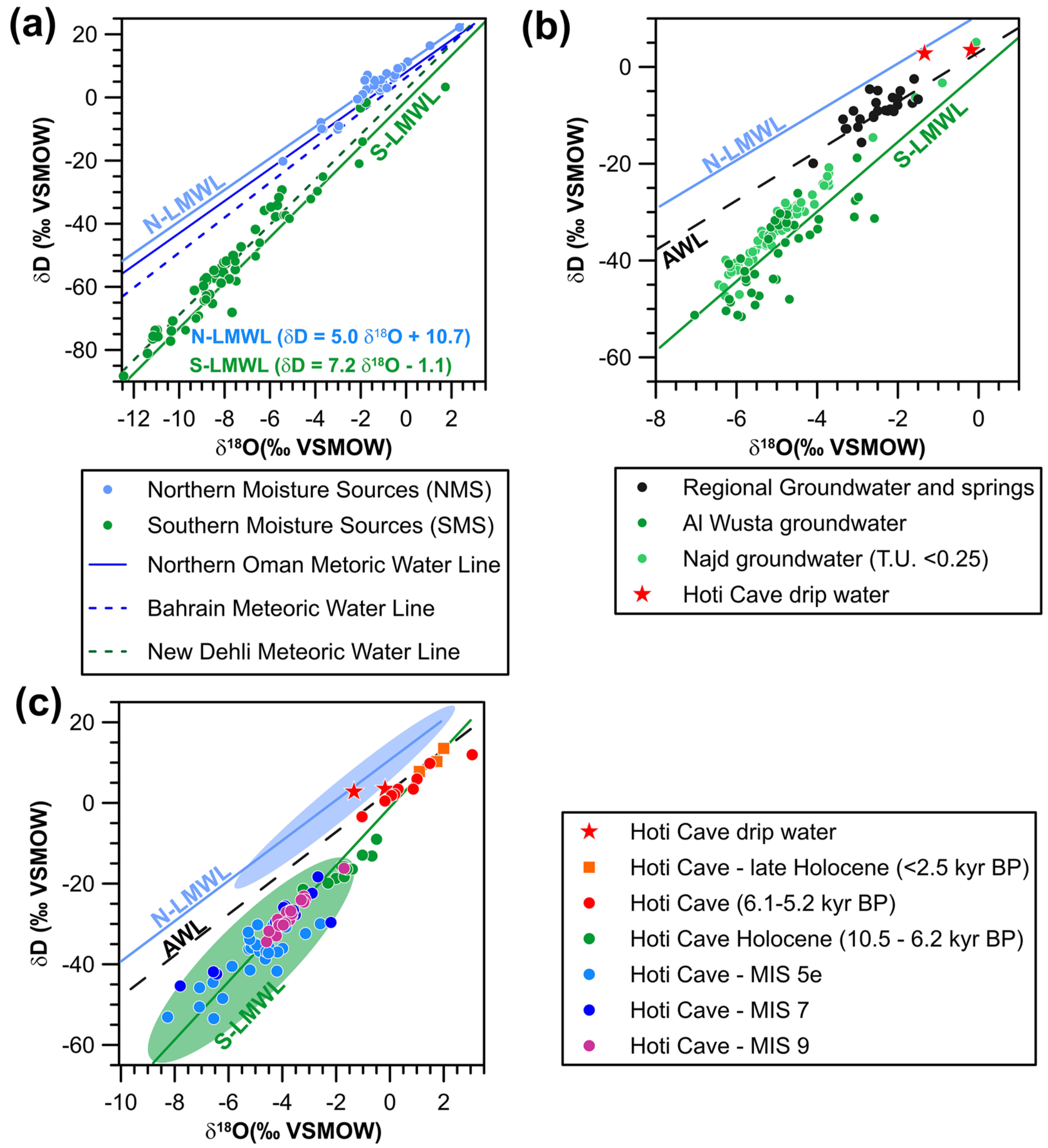

Figure 3. δ^2H and $\delta^{18}O$ values of rainfall, groundwater, cave drip, and fluid inclusion waters from south-eastern Arabia. (a) Modern rainfall samples from Oman (Macumber et al., 1994; Matter et al., 2006; Müller et al., 2019; Weyhenmeyer et al., 2000, 2002). Dots denote individual rainfall events from a northern (blue dots) and southern (green dots) moisture source. Also shown are the two Local Meteoric Water Lines (LMWL) characterizing rainfall originating from a northern LMWL and southern LMWL moisture source in Northern Oman. Northern Oman Meteoric Water Line ($\delta^2H = 5.1\ \delta^{18}O + 8$; Macumber et al., 1997). Dashed lines denote the meteoric water lines for Bahrain ($\delta^2H = 5.5\ \delta^{18}O + 6$; Gat et al., 2001) and New Delhi ($\delta^2H = 7.15\ \delta^{18}O + 2.6$; Pang et al., 2004). (b) Isotopic composition of groundwater from the area around Hoti Cave and cave drip water values (Matter et al., 2006). Also shown are groundwater values from Al Wusta and Najd which were recharged by rainfall from a southern moisture source (SMS). The black dashed line denotes the Akhdar Water Line ($\delta^2H = 5.1\ \delta^{18}O + 3$; Macumber et al., 1997). (c) Isotope composition of fluid inclusion waters extracted from Hoti Cave stalagmites from different MIS. Blue and green shaded areas show the isotopic range of modern rainfall originating from a northern moisture source and SMS.

concomitant change in the calcite fabrics (Frisia, 2015) from columnar-elongated (constant drip rates) to columnar microcrystalline fabrics (more variable drip rates) a few millimeters before the complete cessation of growth of stalagmite H5 (Figures 4a and 4b). This mid-Holocene shift in the moisture source is most likely related to a gradual southward retreat of the ITCZ and the associated ISM rainfall belt (Fleitmann et al., 2007), leading to a complete change in the seasonality of rainfall from a summer to winter/spring rainfall dominated regime as

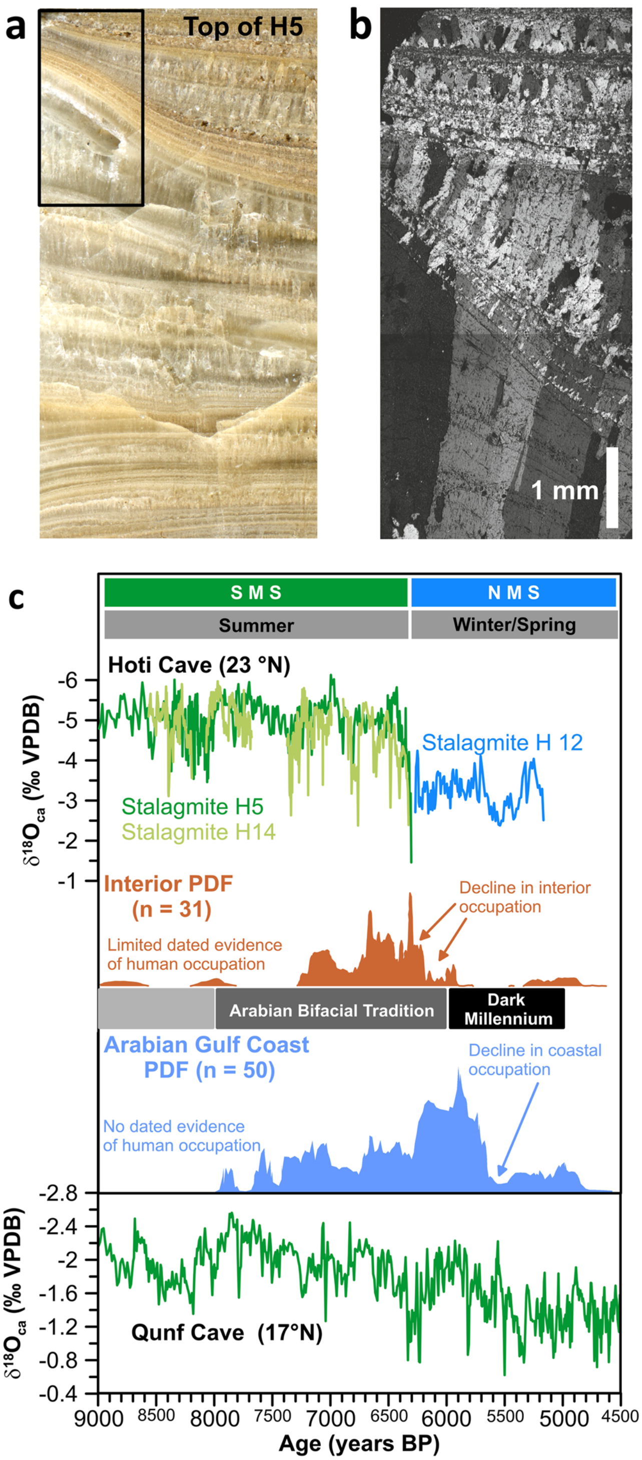

Figure 4. Images of the top of stalagmite H5 and comparison of the Hoti and Qunf Cave isotope records with archeological data from south-eastern Arabia. (a) Image of a polished section of stalagmite H5 and (b) cross polarized thin section image of the uppermost part (the black square in panel (a)). (c) Comparison of the Hoti and Qunf Cave $\delta^{18}O_{ca}$ records with summed probability distribution of ^{14}C dates and archeological periods from south-eastern Arabia (Preston et al., 2015).

indicated by the δ^2H_{fi} and $\delta^{18}O_{fi}$ values (Figures 2 and 3c). Between ~6,300 and 5,200 years BP, Hoti Cave calcite and fluid inclusion isotope values are only slightly more negative than modern ones, suggesting that Northern Oman was only occasionally affected by ISM precipitation. The amount of ISM rainfall was too low to impact the δ^2H_{fi} and $\delta^{18}O_{fi}$ values significantly and the proportion of winter/spring precipitation to groundwater recharge was higher. However, winter/spring precipitation could not compensate for the decline in ISM rainfall and thus total annual rainfall decreased considerably in Northern Oman.

The timing of the wet-dry transition at ~6,300 years BP in Northern Oman is broadly consistent with other proxy records. The Wahalah palaeolake record (UAE; 25°N; Figure 1) places this transition closer to ~5,900 years BP, only slightly later than the Hoti Cave record (Preston et al., 2015). The Awafi palaeolake (25°N) documents a steady increase in detrital sediment flux, change from C3 savannah to C4 grassland, reduced vegetation cover and dune reactivation after ~6,400 years BP (Parker et al., 2004, 2006). Along the east coast of Oman, sediment sequences in lagoons document a collapse of mangrove ecosystems at ~6,000 years BP as a result of a decrease in ISM rainfall (Decker et al., 2020). Thus, most paleoclimate reconstructions from south-eastern Arabia place the major climatic transition between ~6,300 and 5,900 years BP. The slightly diverging age estimates for the abrupt aridification are most likely related to (a) age uncertainties of some paleoclimate reconstructions, (b) their different sensitivities to the increasing aridity, and (c) the geographical position with respect to monsoonal rainfall belt (Fleitmann et al., 2007). In Southern Oman, an area still influenced by the Indian Summer monsoon, the Qunf Cave $\delta^{18}O_{ca}$ record (Figure 4) shows a long-term and gradual decline in ISM precipitation related to a continuous southward retreat of the ITCZ and concomitant weakening of the ISM (Fleitmann et al., 2007). The markedly different evolution of rainfall recorded by the Hoti Cave and Qunf Cave speleothem records is strong evidence for a southward displacement of the monsoonal rain belt.

4.3. Impact of the Mid-Holocene Transition on Human Communities in South-Eastern Arabia

The early to mid-Holocene pluvial period led to an expansion of lakes, wetlands, and vegetation across the Arabian Peninsula (e.g., Parker et al., 2004, 2006; Rosenberg et al., 2011, 2012, 2013). Quantitative rainfall estimates range from 200 ± 50 mm yr^{-1} (UAE) to 400–500 mm yr^{-1} in the Liwa and Wahalah (UAE) regions (Preston et al., 2015) (Figure 1). The Hoti isotope records show that the higher rainfall was caused by a monsoon-type climate until ~6,300 years BP in south-eastern Arabia. The termination of this wet period occurred within a few decades in stalagmite H5 (Figure 4). The Hoti fluid inclusion isotope record reveals a significant decrease or even cessation of ISM rainfall and change from a summer- to a winter/spring-dominated rainfall regime in south-eastern Arabia (Figure 2). Thus, human communities in this region were confronted with two major challenges, a decline in mean annual rainfall and switchover in seasonality. Both factors forced humans to adapt within a few decades to a general decline in the availability of water and food resources, which in turn had also an impact on their seasonal movements in south-eastern Arabia. This adaptation is visible in the archeological records, which document changes in the subsistence and settlement patterns. The period following the mid-Holocene climate change is termed "Dark Millennium" and marks the sudden end of

"Arabian Bifacial Tradition" (ABT) occupation (Figure 4c) (Uerpmann, 2003; Uerpmann & Uerpmann, 1996) as unfavorable environmental conditions for the herder populations of the ABT triggered a migration toward the Gulf coast (Preston et al., 2015). This migration pattern is evident in summed radiocarbon (^{14}C) probability plots from the interior and coastal sites (Figure 4c), supported by an increase in the number of ^{14}C dates from coastal sites and decrease in the number of dates from the interior (Preston et al., 2012, 2015; Uerpmann & Uerpmann, 1996). However, the plots are based on a fairly low number of ^{14}C dates and should be interpreted with some caution. The summed ^{14}C probability plot for the coastal region documents an increase in occupation and sites along the southern Arabian Gulf between ~6,300 and 5,700 years. BP, most likely related to the greater ecological diversity and more abundant freshwater resources in major wadis (Petraglia et al., 2020; Preston et al., 2015). Furthermore, the lack of summer rainfall and disappearance of the mountain pastures, forced nomadic groups to change their migration and settlement patterns (Petraglia et al., 2020; Uerpmann & Uerpmann, 1996).

The mid-Holocene environmental crisis is recorded at the archaeological site of al-Buhais (BHS 18; ~350 km north of Hoti Cave, Figure 1), where occupation ceased after ~6,300 years BP for nearly 1,000 years (Kutterer et al., 2012). Al-Buhais was a central place for mobile herders who were particularly vulnerable to rainfall-induced ecosystem changes. Thus, the abrupt aridification and change in seasonality had an immediate impact on local communities. At BHS 18, around 11% of the studied skeletons dating to ~6,300 years BP exhibited signs of conflict most likely caused by the fierce and violent competition for water from the local springs (Kutterer et al., 2012). The lack of ^{14}C dates after ~6,000 years BP at BHS 18 was most likely caused by the desiccation of the natural spring. The impact of the climatic downturn on communities in Arabia is also supported by genetic investigations, which suggests that Arabian populations experienced a bottleneck at ~6,000 years BP when modern-like climate conditions were established (Almarri et al., 2021). The abrupt mid-Holocene climatic transition in the new Hoti Cave fluid inclusion record reveals a change in the reduction and seasonality of rainfall and therefore helps to develop a more nuanced archeological hypothesis for the observed mid-Holocene settlement shifts in south-eastern Arabia.

5. Conclusions

The new Hoti Cave fluid inclusion record reveals that the early- to mid-Holocene and preceding humid period in south-eastern Arabia was related to an intensification of the ISM. During this time period a significant contribution from a Mediterranean moisture source is not discernible in the fluid inclusion and calcite isotope records. Early- to mid-Holocene Hoti Cave δ^2H_{fi} and $\delta^{18}O_{fi}$ values plot along the S-LMWL for rainfall from the Indian Ocean. A major change in the moisture source and reduction in total annual rainfall occurred at ~6,300 years BP, when monsoon precipitation ceased in the area around Hoti Cave within less than 100 years. The resultant change in the seasonality of rainfall from a summer to a winter/spring regime required fundamental adaptions of Neolithic communities living in this area.

Data Availability Statement

Data are available via the Supporting Information S1, from the corresponding authors and the NOAA paleoclimatology website (www.ncei.noaa.gov/products/paleoclimatology). Age and oxygen isotope data for stalagmite H5 (Hoti Cave) are available via: https://www.ncei.noaa.gov/access/paleo-search/study/9640. Age data and oxygen isotope data for stalagmite Q5 from Qunf Cave are available via: https://www.ncei.noaa.gov/access/paleo-search/study/5541 Age data and stable isotope data for stalagmite H14 (Hoti Cave) are made available via: https://www.ncei.noaa.gov/access/paleo-search/study/9640 and https://www.ncei.noaa.gov/access/paleo-search/study/36735. Fluid inclusion data can be downloaded from https://www.ncei.noaa.gov/access/paleo-search/study/36735.

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