



Human responses to climate and ecosystem change in ancient Arabia

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Recent interdisciplinary archaeological and paleoenvironmental research in the Arabian peninsula is transforming our understanding of ancient human societies in their ecological contexts. Hypotheses about the cultural and demographic impacts of a series of droughts have primarily been developed from the environmental and archaeological records of southeastern Arabia. Here we examine these human–environment interactions by integrating ongoing research from northern Arabia. While droughts and extreme environmental variability in the Holocene had significant impacts on human societies, responses varied across space and time and included mobility at various scales, as well as diverse social, economic and cultural adaptations, such as the management of water resources, the introduction of pastoral lifeways, and the construction of diverse types of stone structures. The long-term story of human societies in Arabia is one of resilience in the face of climate change, yet future challenges include rising temperatures and flash flooding. The history of human responses to climatic and ecosystem changes in Arabia can provide important lessons for a planet facing catastrophic global warming and environmental change.

climate change | droughts | global warming | archaeology | prehistory

Anthropogenic changes to Earth's biological, physical, and atmospheric systems, particularly as a result of global warming (1–3), pose significant challenges to people around the world today (4–7). Archaeologists have dedicated considerable effort to studying human–environment interactions through time, examining how societies have either collapsed in the face of environmental change (8, 9) or transformed themselves in diverse social, political, economic, and material ways to adapt to challenging environments (10–12). Linked to this is research demonstrating that humans have been modifying, reshaping and, in many cases, permanently altering ecosystems since at least the Late Pleistocene, with significant intensification in the Holocene (13–15). Archaeological research is relevant to contemporary debates about climate warming because it demonstrates that the human role in environmental and perhaps climatic transformations began thousands of years ago (16, 17). Archaeology is also relevant because it provides scenarios of real environmental change, and real impacts to and responses by human communities that can help present-day communities understand and more effectively face future challenges on a warming planet (11, 18, 19).

Arabia, situated at the interface between Africa and Eurasia, remains understudied in terms of understanding how human populations adapted to climatic changes. Interdisciplinary archaeological research is nonetheless beginning to provide fascinating glimpses into human responses to the region's sometimes extreme environments and changes (20, 21) (Fig. 1). Pleistocene Arabia saw major climatic shifts that appear to be closely linked to a complex history of hominin occupations (22, 23). Significant improvements have been made in recent years in understanding the relationship between hominin dispersals and Pleistocene occupations through a combination of studies including paleoclimatic

modeling of rainfall patterns (24), remote sensing to identify paleorivers and paleolakes (25), and interdisciplinary field programs (20–23). This work has demonstrated the close relationship between fluctuations in humidity and aridity on the one hand and population expansions, contractions, and extirpations (20, 23, 26) on the other. Here we review the effects of a series of droughts on Holocene populations in eastern Arabia in the light of emerging paleoenvironmental and archaeological records in northern Arabia. In doing so, we assess whether broad correlations between drought events and cultural or demographic changes can be established for the peninsula. We also explore how human populations may have demonstrated resilience by changing lifeways or engaging in landscape management and alteration in response to environmental change. We conclude by briefly addressing current climate forecasts and the challenges they predict for the well-being of people living in Arabia.

Correspondences between Environmental and Archaeological Changes in Southeastern Arabia

The broad outline of Holocene climatic changes and their effects on terrestrial environments in Arabia is well established. Following the extreme aridity of the Last Glacial Maximum, precipitation increased

Significance

Over the last 12,000 y, humans have faced a variety of challenges from climatic variability, either leading to a wide range of technological, economic and cultural responses, or societal collapse. In southeastern Arabia, ancient droughts appear to have corresponded with the decline of inland occupations and population movements to resource-rich areas on the coast, with transformative societal effects. Data from northern Arabia suggest that Holocene populations responded to environmental challenges through high mobility, managing water sources, and transforming their economies. Though more interdisciplinary archaeological data remain to be gathered from Arabia, these examples illustrate diverse strategies to resilience and provide important lessons for a world in which climate predictions forecast dramatic changes in temperature and precipitation.

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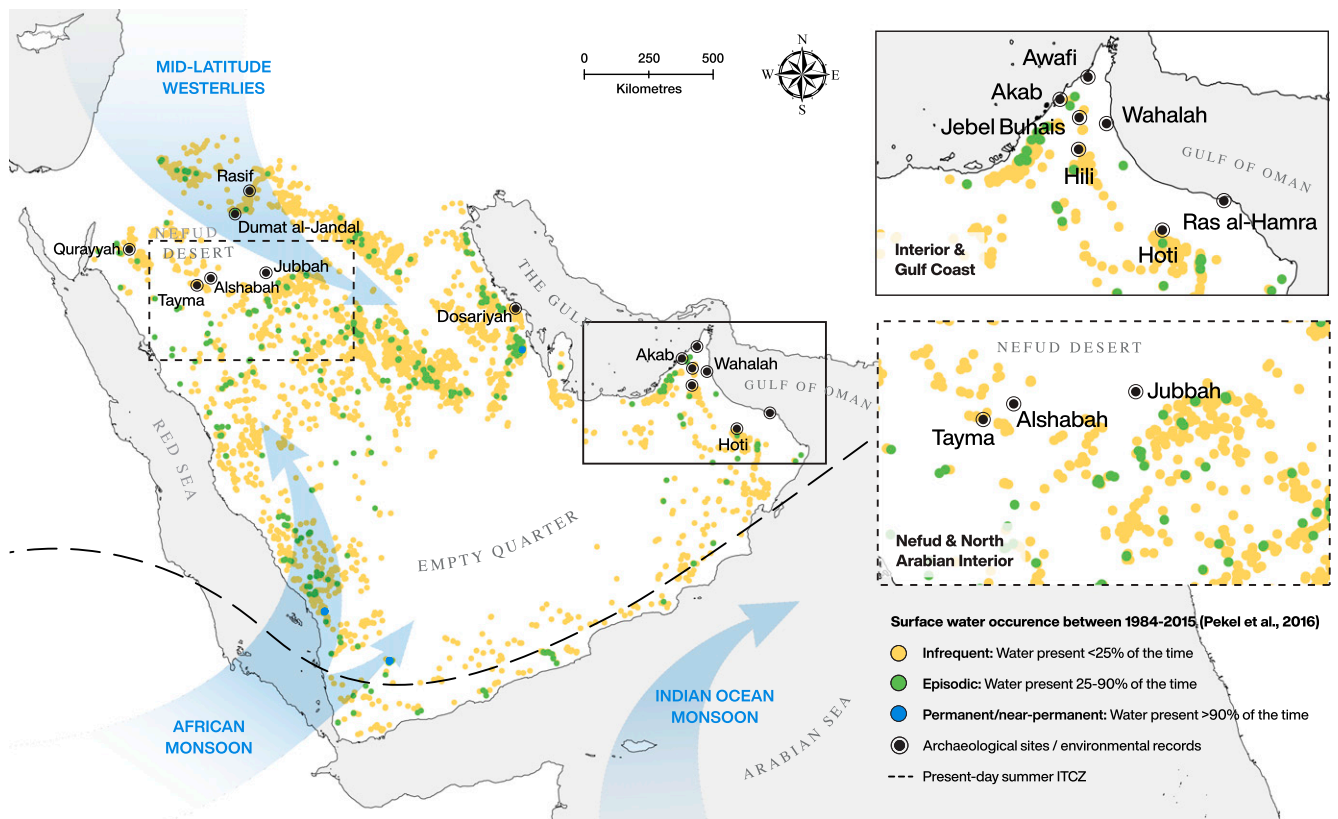


Fig. 1. Map of Arabia showing key archaeological sites and environmental records with map of surface water occurrence between 1984 and 2015 and distribution of water bodies. ITCZ, Intertropical Convergence Zone.

significantly after ~10 thousand years ago (ka) and led to an expansion of paleolakes and vegetation during the Holocene Humid Period (HHP). After ~6 ka, records show a return to aridity, culminating in the establishment of the desert environments that characterize the area today (27–30). Yet, significant variability existed in terrestrial ecosystems across Arabia during particular periods, and lake, dune, and speleothem records show differences in the timing of humidity and aridity events and the degree to which these affected freshwater availability and vegetation patterns. For instance, the HHP was much shorter in northern than southern Arabia, and its termination more abrupt than further south (28).

Researchers working in southeastern Arabia have explored the relationship between environmental change, human demography, and cultural transitions (27, 30) (Figs. 2A and B and 3). Summed radiocarbon dates have been used in southeastern Arabia (27), and in archaeology more widely, in order to reconstruct population trends through time, including assessments of how the relative age frequencies correspond with environmental patterns. Though increasingly used in archaeology, this approach has been critiqued owing to problems with sample size and other inherent limitations (31). Nevertheless, drawing on these radiocarbon proxies, researchers have attempted to explore the link between climate and the relative intensity of human presence along the Gulf coast and in the interior zones of southeastern Arabia, examining these data relative to the timing and spatial extent of abrupt changes in climate from speleothem and lacustrine records (27, 30). Terrestrial records, including the Wahalah and Awafi paleolakes, and the Hoti Cave speleothems, show a number of abrupt changes in rainfall (~8.2 to 8.0 ka, ~7.5 to 7.2 ka, ~6.5 to 6.2 ka, ~5.9 to 5.3 ka, ~4.3 to 3.9 ka), and these have been linked to corresponding shifts in occupation intensity and location based on various datasets including summed radiocarbon dates (30, 32) (Fig. 2A and B). Here we briefly summarize research

drawing on multiple datasets and methodological approaches. We also examine correspondences drawn between arid phases and cultural and demographic changes in southeastern Arabia, providing a context to subsequently evaluate emerging information from interior northern Arabia.

With respect to the early to mid-Holocene humid phase (HHP) in southeast Arabia, various geoarchives record a series of high-amplitude short-term periods of increased aridity (30) (Fig. 2A and B). The climatic downturn between ~8.2 and 8.0 ka BP has been linked to the transition between the earliest Holocene “Qatar B/Fasad” phase and the preceding Neolithic “Arabian Bifacial Tradition” (ABT), which has been interpreted as a shift from hunting and gathering to herding (33), though skepticism has been raised about the pan-Arabian nature of this transition (34). The return to humid conditions around 8 ka corresponds with evidence for an expansion of Neolithic occupation in southeastern Arabia and the establishment of productive herder-fisher communities along the eastern Arabian littoral (30, 35, 36). Further abrupt shifts to drier conditions are also recorded at ~7.5 to 7.2 ka and ~6.5 to 6.3 ka, and seem to correspond with declines in human occupation (Fig. 2A and B). On the coast, however, occupation seems to persist through these climatic downturns, and a maritime trading network linking nomadic pastoralists and foragers in Arabia to Ubaid period sedentary agricultural communities in Mesopotamia was established by the late eighth millennium B.P., continuing until the “Dark Millennium” (~5.9 to 5.3 ka) (21, 37, 38). At Jebel Buhaish (United Arab Emirates [UAE]), burials indicate that the populations were in good overall health, although signs of violence were present (39).

The Dark Millennium describes the sudden end of ABT occupations in southeast Arabia at ~5.9 ka, followed by a paucity of inland archaeological evidence that has been attributed to an abrupt and sustained shift to arid conditions at the onset of the

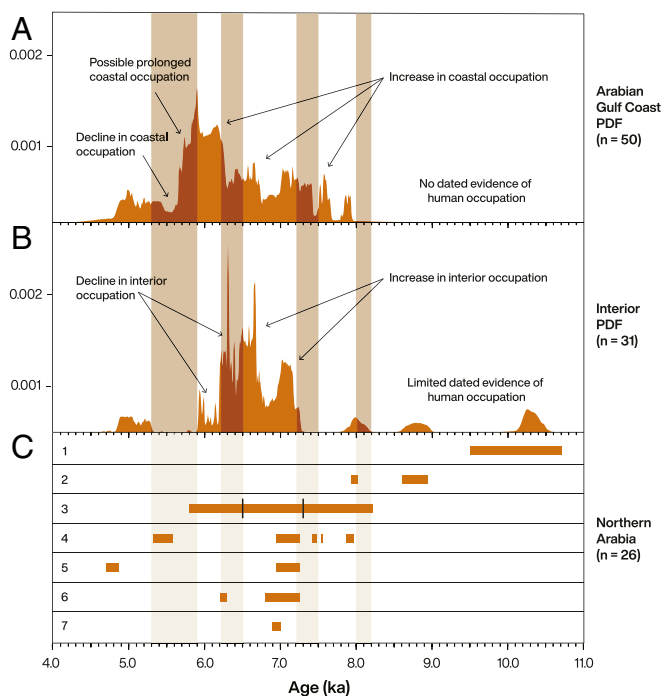


Fig. 2. Comparison of drought events (vertical bars) and archaeological summed probability distributions for southeastern Arabia: (A) Gulf coast sites and (B) interior sites based on ref. 30. (C) Radiocarbon and luminescence ages for archaeological sites in the Jubbah paleolake basin and the Nefud Desert zone (*SI Appendix, Table S1*) 1) Al Rabyah; 2) Jebel Qatar 101/201; 3) Alshabah; 4) Jebel Oraf rockshelter (ORF115); 5) Jubbah cairns; 6) Jebel Oraf 2 (ORF2); 7) NEF-8 stone platform. Nota bene: the vertical bars are darker for southeastern Arabia as these droughts have been recognized in the regional literature; the lighter vertical bars for northern Arabia are for comparative purposes. The black vertical lines between ~7.3 and 6.5 ka are considered the likeliest time of occupation at Alshabah.

mid-Holocene (38). The reduced water availability and vegetation in southeast Arabia created unfavorable conditions for mobile herder populations of the ABT, leading to abandonment of the interior and settlements along the Gulf coast. This intensified use of coastal areas perhaps reflects their greater ecological diversity and water availability (40, 41). Omani coastal populations relied heavily on marine resources, as demonstrated at Ras al-Hamra (42, 43) where bioarchaeological investigations revealed that the population was in poor overall health (44). On the island of Akab in the UAE, dugong bone mound (5.5 to 5.2 ka) excavations revealed that faunal remains were specially arranged, suggesting a monumental space (45), and perhaps the consequence of ritualized acts of consumption at a time of increased subsistence stress (21). The end of the Dark Millennium saw the reexpansion of human populations across the region from ~5.2 ka, and the establishment of Early Bronze Age social, economic, and political systems characterized by the development of oasis agriculture, extensive trade links with Mesopotamia, and construction of thousands of collective burial cairns (21).

The 4.2 ka event and its effect on human occupations has received considerably less attention in Arabia than in neighboring regions, where it is suggested to have contributed to societal collapses (46, 47). Nonetheless, the Awafi and Wahalah lakes between 4.1 and 3.9 ka both indicate reduced humidity at this time (32). This is consistent with other paleoclimate records from Arabia that show major changes in environments between 4.4 and 3.9 ka (48). The abrupt end to humidity at this time, marked by dune reactivation, lake drying, and vegetation loss, corresponds with significant cultural changes in eastern Arabia, and a shift from the

Early Bronze Age Umm al-Nar culture (4.7 and 4.0 ka) to the Middle Bronze Age Wadi Suq cultural period (32). The latter is characterized by fewer settlements and a shift from collective funerary sites and monumental tombs to individual and variable burials (21), and evidence for high rates of subadult mortality, malnutrition, and starvation are recorded at the Hili cemetery (49). This period nonetheless saw the rise of socio-economic and political complexity with the establishment of the Early Dilmun society in and around Bahrain, which emerged as a nexus for long-distance maritime trade with South Asia (35), highlighting the variability of societal responses to the 4.2 ka event across the region (50).

The research conducted in southeastern Arabia over the Holocene has been highly influential among researchers working in the region, illustrative of a close interplay between climate, demographic changes, and societal responses. Yet, the extent to which these patterns can be generalized across the peninsula is currently unclear (30, 32). Given growing knowledge concerning the climatic and environmental diversity of the 3.3 million km² area that makes up Arabia (24), it is essential to examine other subregional archives to understand human responses to a range of environmental changes.

Assessing the Environments and Archaeology of Northern Arabia

Archaeological surveys have demonstrated that northern Arabia saw widespread occupation in the Holocene (21, 22, 51) (*SI Appendix, Fig. S1*). Recent large-scale, interdisciplinary archaeological projects, particularly at the Tayma (51) and Jubbah (23) paleolake basins (*SI Appendix, Fig. S1*), among other key locations (52, 53), have led to important advances in our understanding of the links between human activities, demographic shifts, and climatically driven environmental change.

To obtain a better understanding of the potential spatial distribution of surface water during periods such as the HHP, and how this may have related to patterns of human occupation, we assessed recent surface water across the peninsula (Fig. 1). We compiled a map of all locations on the Arabian peninsula that have evidenced surface water from 1984 to 2015 (54) using Google Earth Engine. We recorded 20,436 discrete locations as holding surface water during this period within Arabia, covering 696 km², primarily on inundated playa surfaces, mostly consisting of episodic (water present between 25 and 90% of the time, $n = 1,441$) and infrequent (water present <25% of the time, $n = 18,986$) occurrences. Although it is unclear how much of the interior had river and lake activation in the HHP, it is of course likely that such water sources were much more frequently available under the increased rainfall regime of the HHP, which may have been around +300% greater than occurs at present, according to hydrological modeling in relation to Tayma (55). Indeed, freshwater distributions may have been more geographically widespread during the HHP, as features that do not activate today would have been recharged by higher groundwater. During the more muted climatic amelioration of the HHP (relative to Late Pleistocene humid phases), it may be that lakes and wetlands were not permanent, with seasonal waters on playa surfaces providing an important primary water source for human populations (25). Moisture receipt in northern Arabia in the HHP is considered to primarily relate to summer monsoonal rainfall, although synchronous intensification of moisture from winter westerly storm tracks and Mediterranean cyclogenesis also has some potential to have reached the northern zones of the peninsula, raising some potential for winter surface water occurrence on pans. Compilation of surface water data is instructive, indicating that the widely distributed playas could have provided Holocene groups some redundancy of water sources, but would have necessitated high mobility to exploit these over geographic space. During periods of elevated aridity during droughts or after the HHP, groups would have sought more

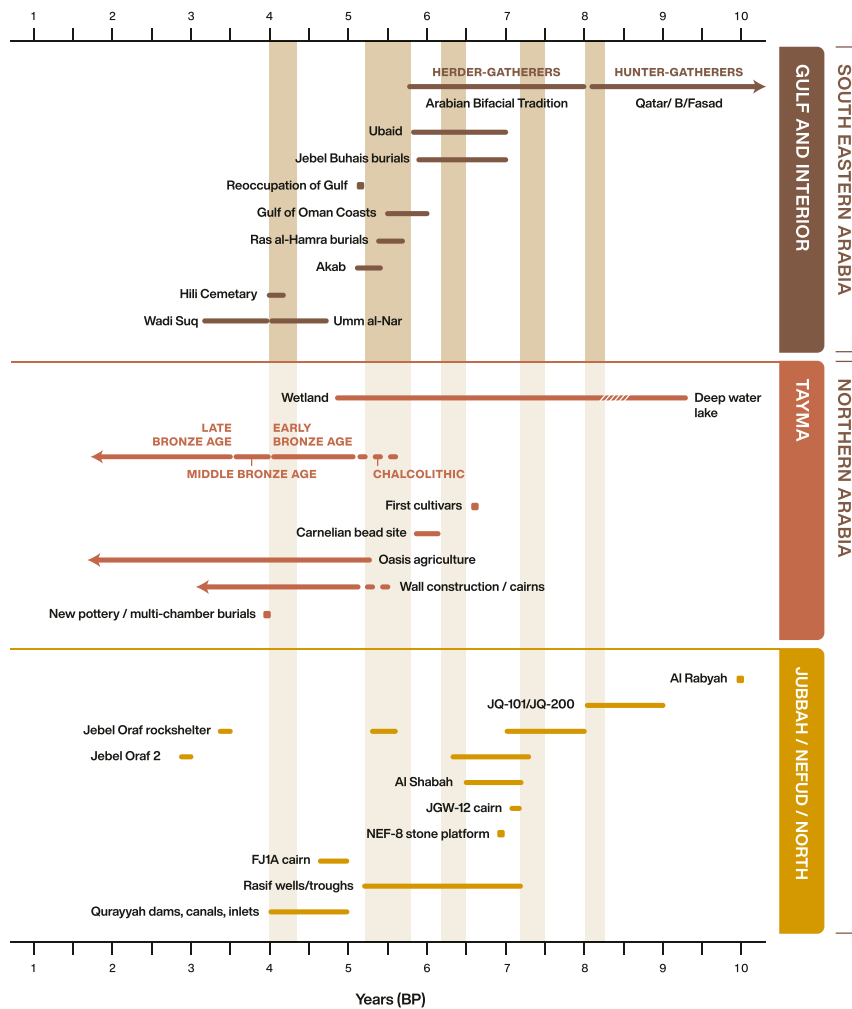


Fig. 3. Timeline of drought events emphasized in studies in eastern Arabia (vertical bars) and key archaeological sites and cultural transformations across the peninsula. *Nota bene:* the vertical bars are darker for southeastern Arabia as these droughts have been recognized in the regional literature. The lighter vertical bars for northern Arabia are for comparative purposes and do not necessarily designate the presence of the same droughts. The dashed lines indicate earlier possible onsets of events.

permanent water bodies in the interior or along coastal margins, where discharge of local aquifers would have been activated.

Northern Arabia is home to two key oases that have seen long-term human occupation: Tayma and Jubbah. Permanent water may have been available at both oases, where surface water may have been more persistent due to shallow recharged groundwater levels. This natural access may potentially have been coupled with wells excavated into the upper aquifers during more arid periods. Jubbah is a dune-bounded endorheic basin that measures $\sim 20 \times 5$ km with deposits extending to a depth of ca. 30 m (56–58). At Jubbah, there are no inflowing drainage channels, which suggests that the water bodies formed as a result of surface expression of water from the shallow Saq aquifer, recharged by both local and regional rainfall onto the dune field. An endorheic depression is present at Tayma with an area of almost 20 km² (55). Holocene lacustrine deposits are represented by a vertical range of 17 m and are interpreted to be the remnants of a perennial water body.

At the end of the Pleistocene, a shallow lake was present at the Jubbah oasis at ~ 12 ka (56) and a series of dated Holocene sites is found across the basin (Figs. 2C and 3 and *SI Appendix, Fig. S1 and Table S1*). The site of Al Rabyah contains the first identified Epipaleolithic stone tool assemblage in Arabia, similar to “Geometric Kebaran” assemblages from the Levant, although

several thousand years younger (~ 10 ka) (56). Near Jebel Qattar (JQ) at Jubbah, an early phase of lake formation at JQ-200 is dated to between ~ 8.7 and ~ 8.0 ka (59) and suggests continued water availability in Jubbah across the 8.2 ka event. Next to this lakebed, a large and diverse lithic assemblage was recovered at JQ-101, which included points similar to those previously known from the Pre-Pottery Neolithic (PPN) of the Fertile Crescent, suggesting that a long period of time is represented at the site. These finds are 500 km south of their previous range, pointing to either movement of peoples or the exchange of ideas over this large geographic area between ~ 10 and 8 ka. The introduction of domesticated livestock into northern Arabia, probably from the Levant, is evidenced in the rock art at Jubbah (60).

At Jebel Oraf 2, southwest of the main Jubbah basin, a shallow paleolake existed as early as ~ 8.5 ka, with a high-stand at ~ 7.3 ka (61, 62). More than 170 hearths were recorded along the lake-shore, showing repeated occupations from ~ 7.2 ka until at least 6.3 ka (Fig. 2C). At the nearby Jebel Oraf rockshelter, archaeological deposits were dated to 8.0 to 7.0 ka (62) (Fig. 2C). Mobile pastoral occupations were also identified at Alshabah, in the western Nefud Desert, dating to ~ 7.3 to 6.5 ka (63) (Fig. 2C). At Alshabah, pastoralist groups were able to exploit a seasonal interdune setting deep in the Nefud Desert, around a small, likely seasonal, playa. This highlights their extensive knowledge

of the landscape and the ability of pastoralist groups to respond to localized rainfall events and dynamic surface water availability, of the form demonstrated by our water distribution analysis (Fig. 1). Lithic materials at the site show the use of small clasts from a wide range of geological exposures, consistent with a highly mobile group (63). The presence of human groups at Jubbah oasis and in the Nefud Desert across the 7.5 to 7.2 ka and 6.5 to 6.2 ka periods indicates that wetlands and paleolakes in this area likely supported the survival of human groups during periods when other parts of Arabia experienced aridity. The accumulation of ephemeral hearths and an absence of architectural remains at Jebel Oraf and at Alshabah (61–63) appears to reflect a wider pattern where high mobility enabled the exploitation of seasonal and unpredictable resources. The presence of fragmentary finds of *Bos* sp. at Jebel Oraf 2 (61, 62) and at the Jebel Oraf rockshelter, together with the presence of caprid at Alshabah (63) and at the Jebel Oraf rockshelter, indicates that these groups likely incorporated domesticates into their economy.

At Tayma, a freshwater paleolake was present between ~9.3 and 8.5 ka, with water ~13 m deep (55). Significant lake shrinking is recorded between 8.5 and 4.8 ka, reflecting a shift from a deepwater lake to a wetland environment with fluctuating availability of surface water (55). Pollen records from Tayma give a somewhat different chronology but similar sequence, and suggest that the period of ~8.7 to 8.0 ka marked the wettest conditions of the Holocene, with much drier conditions in the period from ~8.0 to ~6.3 ka, when grasslands retreated and more drought-resistant desert shrublands spread (64). The first indications of cultivated plants—such as grapes and figs—are from around 6.6 ka (51, 65, 66). The period ~6.3 to 5.9 ka saw slightly wetter conditions. A carnelian bead manufacturing site located on the margins of a wetland, dating to ~6.2 to 5.9 ka (51, 55), falls in this somewhat wetter period. To date, no archaeological sites coinciding temporally with the ~6.5 to 6.2 ka arid event of eastern Arabia have been identified, but early and mid-Holocene archaeology has not been a focus of research for groups working in the area. As discussed below, the continued presence of pollen from domesticated plants at Tayma after their first appearance suggests human occupations occurred from 6.6 ka onwards, including through arid periods. While it is notable that Tayma had freshwater resources and vegetation in the early and middle Holocene, there is currently little to say about the potential impact of arid phases between 8.2 and 6.6 ka on human groups.

A wide variety of stone structures (e.g., kites, gates, wheels) were constructed across northern and western Saudi Arabia (for example, ref. 67), likely in the early to middle Holocene, and these appear to have been revisited and rebuilt over thousands of years. Their function is debated, though kites are often interpreted as animal traps (68, 69). These stone structures have rarely been dated, though kites were constructed as early as 10 ka in Jordan (70), suggesting that the stone structures of Arabia may have seen construction and use across much of the Holocene. Cairns have been dated at Jubbah from ~7.2 ka (JGW-12) and to ~4.85 ka (FJ1A), occurring in both Neolithic and Bronze Age settings (60), and a stone platform (NEF-8) in the Nefud Desert was recently dated to ~7.0 ka (Fig. 2C). These diverse stone structures demonstrate economic intensification, including a focus on animal management, and sociopolitical changes reflected in an increased attachment to particular places in the landscape, albeit within the context of mobile societies.

While some evidence supports continued water availability in basins like Jubbah, there are also indications that northern Arabian communities were actively managing water sources by the fifth millennium BC. For example, Chalcolithic groups at Rasif excavated shallow wells and constructed complex trough systems, which were still in use in the fourth millennium BC (52). Hydrological studies in the oases of Tayma and Dumat al-Jandal likewise indicate water provisioning mainly from ground water,

with utilization of surface runoff by means of dams (71, 72). Such strategies allowed groups to transcend short-term fluctuations in the availability of surface water.

Understanding of the impacts of the Dark Millennium arid phase in northern Arabia is in its infancy, though the absence of paleolake deposits in the Nefud Desert at this time is suggestive of aridity in northern Arabia (35). Nonetheless, our ongoing archaeological investigations at the Jebel Oraf rockshelter (62) in the Jubbah basin date human occupations to between ~5.6 and 5.3 ka (Fig. 2C), falling squarely within the Dark Millennium. Hunted and domesticated fauna and abundant grinding stones are present at the site.

At Tayma, freshwater was available in a wetland environment between ~8.5 ka and 5 ka, including through the Dark Millennium (55). Although there is a gap of dated archaeological sites between the carnelian bead workshop at ~6 ka and the onset of permanent settlement and wall construction beginning in the Early Bronze Age by ~5 ka (51), pollen data suggest continual cultivation from the midseventh millennium BP onwards (66) indicating that human occupation of the basin likely continued through the Dark Millennium. Hausleiter and Eichmann (51) distinguish between an initial phase (from ~6.6 ka) of ‘oasis cultivation’, and subsequent Bronze Age ‘oasis agriculture’, characterized by much more intensive occupation of the basin and cultivation of an increasingly diverse array of plants in the context of a sophisticated water management system. The Tayma oasis would come to have a wall system more than 18 km in length, which may have been built for multiple purposes, from defense to reduction of sediment mobility. The northwest Arabian oasis of Qurayyah also saw construction of monumental stone walls in the Early Bronze Age, and there are indications that these enclosed agricultural fields and canals (53). The beginnings of oasis agriculture, premised on sophisticated water management, probably developed gradually in the context of a trend toward aridification after the peak of the HHP (i.e., after ~8 ka at Tayma). It is also possible that overgrazing compounded the effects of climate change, as argued for southern Jordan (73), potentially forcing a diversification of the economy and the establishment of agriculture.

The Jubbah basin contains evidence of populations in the region both before and after the 4.2 ka event, yet few sites have chronometric ages and thus few data are available to evaluate possible occupation across this drought. The archaeological evidence at Tayma is stronger, however, and occupations are considered to represent an “unbroken sequence” from the beginning of the Bronze Age in the third millennium BC to the Iron Age in the 11th century BC (51) including through the 4.2 ka event. Other sites in northwest Arabia demonstrate long term habitation as well as considerable evidence of water management (72). By the late third/early second millennium BC, the transition to the Middle Bronze Age occurred at Tayma, in which graves feature a variety of Bronze weapons. Contemporary burials and weapons were also found at Qurayyah (51), suggesting the possibility of regional cultural traditions featuring an emphasis on warrior and elite culture.

Taken altogether, interdisciplinary archaeological and paleoenvironmental research in northern Arabia is contributing data on the relationship between climate change and human societal development in the Holocene. This information can now be used as the basis for exploring points of similarity and contrast with the record from southeastern Arabia.

Discussion

A main aim here has been to explore how different populations in Arabia responded to the challenges of environmental change, which is now possible owing to concerted interdisciplinary efforts in several areas (Fig. 3). That said, it must be noted that although interpretations about human–environment interactions are offered here, there is a critical need to conduct integrated and

interdisciplinary research to fill chronological gaps particularly between 5,000 y ago to the present, where little interdisciplinary data are available. Nevertheless, some environmental and cultural trends are apparent, and differences between regions can be teased apart. In northern Arabia, the large endorheic basins at Jubbah and Tayma appear to have acted as ‘hubs’ during climatic downturns, whereas populations in southeastern Arabia sought out coastal resource locations during droughts. The regional contrasts are perhaps best illustrated by examining the different responses to the ‘Dark Millennium’. In southeastern Arabia, the ‘Dark Millennium’ corresponds with widespread depopulation of the interior and a shift to coastal occupations (30, 38, 41) (Figs. 2A and B and 3). In contrast, the record from northern Arabia shows a somewhat different trajectory. At Jubbah, there is evidence of occupation at the Jebel Oraf rock-shelter, whereas at Tayma there is evidence for Chalcolithic settlement, the onset of oasis agriculture and the early beginning of wall construction (Fig. 3). In other areas of northern Arabia, such as at Rasif, people began to capture runoff through construction of landscape features and excavation of wells (52). Such developments encapsulate a key difference between northern and southeastern Arabia: in the north the presence of large and shallow aquifers facilitated survival through climatic downturns, when technological and social practices enabled their access. In contrast, less extensive aquifers in the southeast seem to have contributed to a more direct correspondence between environmental and societal changes (Fig. 3). This is, however, not to say that climatic shifts did not impact populations in interior and northern Arabia. For instance, at Tayma the Early to Middle Bronze Age and associated changes in material culture and burial practices correspond temporally with the changes occurring across the 4.2 ka event (51). It may therefore be that the story in the interior is better characterized in terms of societal reorganization, contrasting with the more abrupt demographic changes seen in the southeast.

Although a difference in research focus has led to somewhat different time periods being investigated at Jubbah and Tayma, the combined record illustrates human habitation in the Nefud Desert region from ~9 ka until the present. The archaeological record on the fringes of the Jubbah oasis (Jebel Oraf) and in the western Nefud Desert (e.g., Alshabah) indicate human presence from ~9 ka to 5.3 ka and suggests that hunter-gatherers and pastoralists responded to environmental changes across climatic changes and across localized and peninsula-wide droughts well before the shift to oasis-centered agriculture. That droughts would have been felt severely is without doubt and can even be witnessed in the rock art, where starving cattle are documented at Shuwaymis (74). Extensive use of dog-assisted hunting is also visible in the rock art throughout the Holocene, and would have presented further insurance against droughts by securing better hunting success (75). In addition, the abundance of hearth sites likely illustrates a high degree of mobility in the Arabian interior, reflecting the seasonal exploitation of water sources and vegetation in the extensive sand seas. To date, no architectural remains dating to this period have been documented in the Nefud Desert, and even the use of tents cannot be proven as sites lack postholes, and hearths were likely only in use for a very short period of time (61, 62).

Initially, the ability to move gave populations across Arabia a great deal of flexibility in the face of climatic and environmental change, yet as socio-political complexity developed and societies invested heavily in particular places (oases, stone structures across the landscape, wall construction) the desire or ability to move became more limited. For example, though in good overall

health, 14% of the juvenile and adult burials from Neolithic Jebel Buhais show marks of fatal trauma (39). This has been interpreted as the result of competition for grazing lands. Technological solutions – digging for water, then digging deeper; developing irrigation, then developing better irrigation—would have helped buffer climatic variability, but would also have established contexts of ownership that may in turn have intensified the defending (and attacking) of territories. In addition, periods of increased productivity would have led to population growth, followed by stress when productivity and resources decreased as a result of reduced water availability during arid periods.

Researchers are increasingly paying attention to how archaeological data inform on contemporary issues, including human–environment interactions. The Arabian archaeological record is a case in point, indicative of diverse human responses to environmental changes. For millennia, mobility was the main human response to environmental variability. But with increased population sizes and an increasing investment in place, options for human mobility have decreased over time. While accessing groundwater was an innovative solution in the past, allowing oasis settlements to flourish, the rapid depletion of these aquifers in recent years highlights the need for sustainable solutions to meet environmental challenges. Moreover, since 2001, land surface temperatures in Saudi Arabia have increased by up to 1.2 °C (76). Models of future Arabian climate indicate that temperatures are expected to rise, while rainfall will reduce, and be more situationally extreme, leading to flash flooding (77–79). Traditional systems of water management are being recognized as one potential way to mitigate current and future problems. For example, oasis agriculture and irrigation systems are being recognized, such as Globally Important Agricultural Heritage Systems (GIAHS) by the United Nations (80). The UAE government has made significant attempts to keep sustainable agricultural practices and technological traditions alive by recognizing the “Al Ain and Liwa Historical Date Palm Oases” as United Nations Educational, Scientific and Cultural Organization (UNESCO) and GIAHS properties. In this case, both food security and sustainability are closely linked with historical practices and capacities for local decision-making, oversight, and control of palm-based food resources (i.e., dates) (80). This shows that knowledge drawn from historical practices and archaeological sources can in fact contribute to addressing contemporary challenges (81).

The record of ancient Arabia provides evidence of extreme environmental change and how these impacted human societies. This emphasizes the serious challenges of climate change and demonstrates the myriad ways in which humans can build resilience. Human responses to climate change were not predictable in a simple, linear fashion, but rather complex processes of social and political restructuring took place through the filters of major environmental changes, both climate caused and anthropogenic. While future challenges to areas such as Arabia will of course be different in character to those encountered in prehistory, they nevertheless reflect the same basic categories of processes. In that sense, learning about different manifestations of past climate, societal resilience, and vulnerability provides valuable lessons for the future.

Data Availability. All data discussed in this paper are available in cited references and in *SI Appendix, Table S1*.

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