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Review Article

# Consequences of Climate Change from the Past to the Present: Implications of Paleoclimate Research in Archaeological Studies

**Babak Shaikh Baikloo Islam**
PhD in Archaeology; Researcher in Paleoclimate Studies.

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**Abstract:** Climate change caused by global warming is one of the most important global challenges of our time, and has wide-ranging effects on the environment and human societies. This study highlights the various consequences of climate change and also emphasizes the importance of a paleoclimatological approach in archaeological studies. By integrating paleoclimate data and archaeological evidence, we can gain deeper and clearer insight into how ancient cultures and civilizations adapted to climatic events. In addition, with a comprehensive understanding of the possible consequences of this phenomenon, we will be able to overcome the problems related to current climate change. This article first discusses the effects of climate change on the ecosystems, agriculture, subsistence, and human health by citing cases from around the world. Then it deals with the methodology of paleoclimate research as the results of these high-resolution studies provide a more accurate and comprehensive understanding of the complex relationship between climate and humans.

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## 1. Introduction

The current phenomenon of climate change, driven by the accelerating trend of global warming, has emerged as a critical global issue with profound implications that increasingly challenge both natural and human systems. The Intergovernmental Panel on Climate Change (IPCC) has extensively documented the ongoing alterations in the Earth's climate, primarily attributable to anthropogenic activities such as fossil fuel combustion, deforestation, and industrial processes (IPCC, 2021, 2022). These transformations—largely a consequence of exponential population growth over the past 150 years—are manifested through rising global temperatures, shifting precipitation patterns, increasing frequency of extreme weather events, and the rise in mean sea levels (Nicholls & Cazenave, 2010). Understanding the implications of these changes necessitates a multidisciplinary approach that integrates insights from paleoclimatology and archaeology. In other words, knowledge of the past can provide valuable foresight into the potential consequences of the ongoing climatic crisis.

Climate change archaeology, as an emerging and significant field of study, offers critical insights into contemporary discussions surrounding global climate change. Despite several decades of employing paleoclimatic research within archaeological investigations, the potential contributions of this interdisciplinary perspective to current debates—such as those addressed by the IPCC—have remained relatively underexplored (Van de Noort, 2011; Roscoe, 2014). Archaeology has the capacity to enhance our understanding of socio-environmental resilience, adaptive capacity, and societal robustness by examining analogous periods in the past (Van de Noort, 2011). Archaeological research provides unique opportunities to observe human–environment interactions under diverse climatic regimes across various spatial and temporal scales.

Given the technical sophistication of modern climate models, they often fall short in representing the dynamics of human social behavior. Crucially, archaeology underscores the significance of cultural diversity as a key source of resilience and proposes alternative strategies for agricultural and industrial practices. Integrating archaeological perspectives into climate change research can offer the essential long-term temporal context needed to refine and strengthen existing climate models (Roscoe, 2014; Burke et al., 2021). This paper discusses the recognized consequences of climate change and emphasizes the role of paleoclimatic research within archaeological studies, as this approach provides a more scientific and comprehensible framework for analyzing the emergence, transformation, and decline of past cultures and civilizations.

## 2. Methodology

This study adopts an interdisciplinary methodological framework to examine the multifaceted consequences of climate change and to elucidate the significance of a paleoclimatological approach in archaeological research. The analysis focuses on the direct, indirect, and cascading (domino-like) impacts of extreme climatic events, which tend to intensify during periods of climatic instability and often coincide with profound environmental and social transformations. In this context, reference is made to historical and prehistoric examples of Holocene climatic events, which provide valuable insight into the complex relationship between climate variability and cultural change in ancient societies. Furthermore, the study highlights the necessity of incorporating paleoclimate research into archaeological analyses and presents a concise overview of paleoclimatological methodology. This section outlines the principal data sources and tools of paleoclimate reconstruction, including the use of proxy records generated from different archives such as lacustrine sediments, ice cores, speleothems, and tree rings, and demonstrates how integrating these datasets with archaeological evidence can enhance our understanding of past climatic conditions and human adaptive mechanisms. Overall, the study aims to establish an interpretive framework that connects long-term climatic data with cultural evidence, thereby contributing to a deeper comprehension of human–environment interactions in the past and offering valuable perspectives for interpreting contemporary climatic challenges. It is worth noting that ChatGPT was used to enhance the manuscript text, and Napkin was employed to create Figure 3.

## 3. Implications of Climate Change

### 3.1. Ecosystem Disruptions

Climate change induces significant disturbances across global ecosystems, resulting in alterations to the geographical distribution of plant and animal species, habitat transformations, and the loss of biodiversity (Pecl et al., 2017; Sharafi et al., 2014). During the current period of global warming, rising temperatures have prompted numerous animal species to migrate toward higher latitudes or elevations where cooler climatic conditions prevail, to maintain their ecological and physiological balance (Parmesan & Yohe, 2003; Pecl et al., 2017). Elevated temperatures also trigger earlier plant blooming, potentially leading to phenological mismatches between plants and their pollinators (Walther et al., 2002).

Environmental changes associated with ongoing climate shifts are occurring at an accelerating pace and are affecting biodiversity through mechanisms such as habitat loss and fragmentation, biological invasions, and eutrophication (Sharafi et al., 2014). The impacts of climate change vary across terrestrial, freshwater, and marine ecosystems, altering species richness and interspecific equilibria, which can, in turn, disrupt ecosystem functionality (Molefhi, 2021). These transformations have far-reaching consequences for the environment, human well-being, and even the climate system itself, influencing food security, disease transmission, and atmospheric carbon storage (Pecl et al., 2017; Sugden, 2017).

The repercussions of climate change on biodiversity and ecosystem services underscore the necessity of implementing adaptation and mitigation measures at individual, governmental, and international levels (Molefhi, 2021). Without coordinated and proactive interventions, the long-term consequences may exacerbate ecological degradation and potentially lead to irreversible ecosystem collapse. Key examples of environmental threats include the following:

Coral Reefs: Coral reef systems represent some of the most vulnerable ecosystems to climate change. Ocean warming causes coral bleaching, leading to extensive biodiversity loss and habitat degradation (Hughes et al., 2017).

Arctic Ecosystems: In the Arctic, the melting of sea ice and permafrost is transforming habitats for species such as polar bears and seals. These changes also endanger other native organisms that depend on these keystone species for survival (Hassol & Corell, 2006).

### 3.2. Sea-Level Rise

The melting of glaciers and polar ice sheets, a result of global warming, contributes substantially to the rise in ocean and sea levels, posing a significant threat to coastal communities worldwide. Estimates suggest that, depending on the trajectory of greenhouse gas emissions, global sea levels could rise by up to one meter by the year 2100 (Nicholls et al., 2018). This rise is expected to accelerate coastal erosion, increase the salinity of freshwater resources, and generate severe risks for both human populations and ecosystems in coastal regions (Navarro, 2021), potentially leading to large-scale forced migrations.

Glaciers and ice caps play a major role in this process. Recent assessments indicate that between 2003 and 2010, they contributed approximately 0.41 ± 0.08 mm per year to global sea-level rise (Jacob et al., 2012). The ongoing and potentially accelerating melting of ice masses is projected to further intensify this phenomenon (Church et al., 2007). In addition to ice melt, the thermal expansion of seawater caused by global temperature increases also significantly contributes to rising sea levels.

This combination of factors—together with the growing frequency of extreme weather events and higher wave surges—amplifies coastal erosion, flooding, and the overall risks associated with habitation in low-lying coastal areas (Navarro, 2021). Examples of hazards associated with sea-level rise include:

The Nile Delta: Archaeological sites along the Nile Delta are increasingly vulnerable to sea-level rise and heightened flood risks. These changes threaten not only modern settlements but also ancient and historical sites of considerable cultural heritage value (Shaltout & Azzazi, 2014).

Venice: The city of Venice has been experiencing recurrent flooding events exacerbated by climate change, which are damaging its unique architecture and cultural heritage (Lionello et al., 2021).

### 3.3. Extreme Weather Events

Climate change is intensifying the frequency and severity of extreme weather events, including storms, droughts, torrential rainfall, and heat and cold waves (Fig. 1). Such events can devastate human settlements and infrastructure, force population displacements, trigger famine and food insecurity, and, overall, pose profound challenges to both human societies and natural ecosystems. Research indicates that ongoing anthropogenic climate change has already led to significant temperature increases and a higher recurrence of extreme precipitation events (Stott, 2016).

Extreme or anomalous climatic events can inflict severe damage on the socioeconomic systems of affected communities (Mirza, 2006). Climate-related hazards—such as droughts, heatwaves, cold spells, and heavy cumulative rainfall leading to floods—exert considerable impacts on food security, livelihoods, and public health, particularly among vulnerable populations (Coghlan et al., 2014).

Overall, the consequences of climate change and the damages resulting from extreme weather events are extensive and profound (Fig. 2). Current projections suggest that anthropogenic climate change will continue to intensify the frequency and magnitude of such events in the future (IPCC, 2022). The growing vulnerability of social infrastructure to climatic and environmental fluctuations underscores the urgent need for effective adaptation measures and mitigation strategies (Easterling et al., 2000).

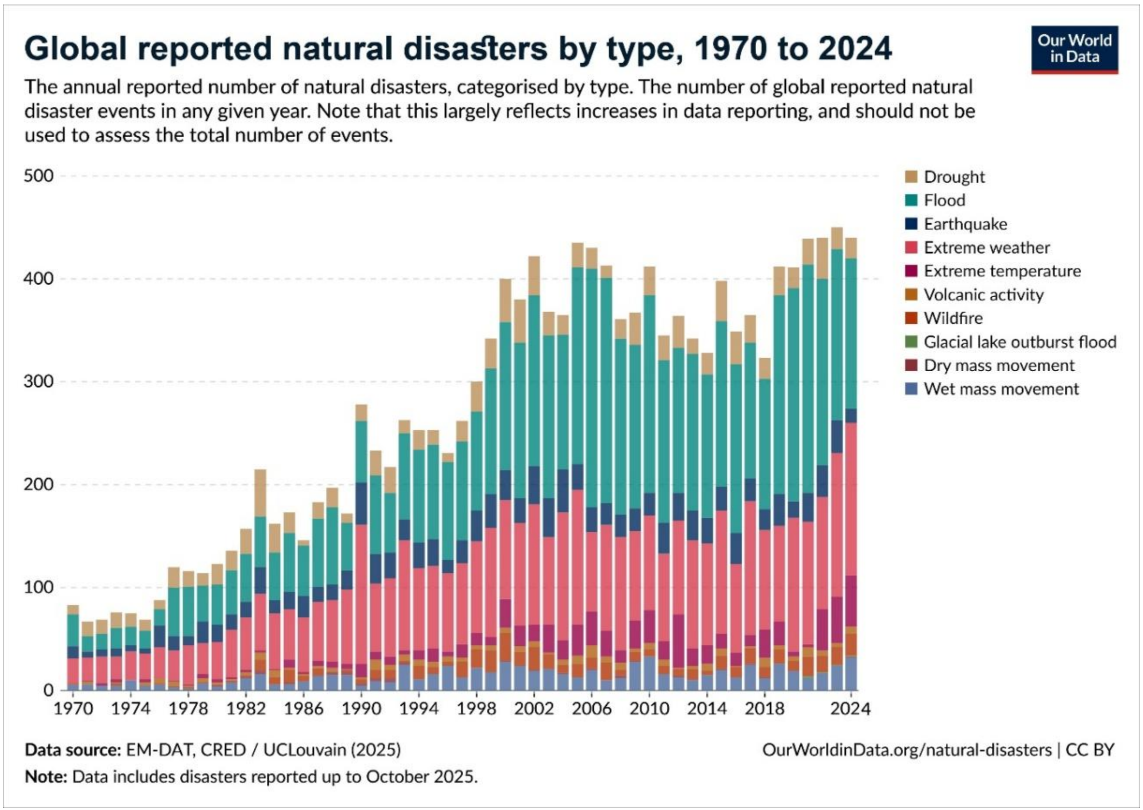


Figure 1. Global frequency of natural hazards—including droughts, floods, extreme weather events, temperature extremes, and wildfires—associated with contemporary climate change driven by global warming, from 1970 to 2024 (Source: https://ourworldindata.org/grapher/natural-disasters-by-type)

### 3.3.1. Hurricanes

In recent decades, the intensity of hurricanes has increased due to ocean warming. For instance, Hurricane Katrina in 2005 caused widespread destruction in New Orleans, underscoring the vulnerability of urban areas to climate-related atmospheric hazards (Kunkel et al., 2013). Hurricanes have a profound impact on the environment, society, and economy of coastal regions. Climate change is expected to alter hurricane patterns and potentially amplify their frequency and intensity, leading to fundamental transformations in coastal wetland ecosystems that affect hydrology, geomorphology, and biotic structures (Michener et al., 1997).

From an economic perspective, hurricane-related damages and losses in the United States are projected to increase by approximately 10 billion USD annually as a result of global warming (Nordhaus, 2010). Socially, hurricanes can induce long-term transformations in coastal communities. For example, in the island of Saint Martin, exposure to coastal flooding has intensified (Gargani et al., 2020). The case of Hurricane Katrina further demonstrated how such extreme events can exacerbate pre-existing social inequalities and wealth disparities (Petterson et al., 2006). These impacts collectively highlight the critical need for interdisciplinary research and a comprehensive understanding of the consequences of climate change in coastal environments (Michener et al., 1997).

### 3.3.2. Droughts

Historically, prolonged droughts have been closely associated with social collapse. The decline of the Classic Maya civilization has been linked to severe and consecutive drought events during the

Late Classic period (Hodell et al., 2005; Douglas et al., 2016). Similarly, the collapse of the Akkadian Empire in Mesopotamia (Cullen et al., 2000; Weiss et al., 1993), the gradual decline of civilizations in the Indus Valley and southeastern Iran (Safaierad et al., 2024; Shaikh Baikloo, 2021a), as well as the First Intermediate Period in ancient Egypt (Younes & Bakry, 2022), have been explained in relation to the 4.2-kiloyear drought event (2200–1900 BCE) (Weiss, 2016, 2017; ).

Droughts driven by climate variability exert substantial socio-economic and environmental impacts. They can cause agricultural losses, increase fiscal pressures on governments, and elevate insurance claims (Yang et al., 2023). Drought disproportionately affects poorer populations, resulting in water and food shortages, forced population displacement, and heightened health risks (Ülker et al., 2018). In Mexico, historical droughts have significantly impacted the agricultural sector and rural populations, rendering specific regions highly vulnerable (Safaierad et al., 2025; Kennett et al., 2022; Douglas et al., 2015). These effects can be particularly severe in areas with limited resources, potentially precipitating humanitarian crises (Yang et al., 2023).

Interestingly, while droughts may devastate economically disadvantaged communities, wealthier segments can sometimes benefit, potentially contributing to the emergence of a new middle class (Rao, 2022). Addressing these challenges requires a holistic approach, including improved water management, early warning systems, and sustainable agricultural practices (Yang et al., 2023). The Syrian civil conflict illustrates how drought can act as a catalyst for social unrest and political instability (Ülker et al., 2018).

#### 3.3.3. Extreme Rainfall Events

Climate change is projected to increase both the frequency and intensity of extreme rainfall, leading to more frequent local flooding. However, attributing the rise in flood occurrence directly to anthropogenic climate change remains challenging due to low confidence in current predictive models (Kundzewicz et al., 2014). The socio-economic impacts of severe flooding are substantial and are exacerbated by population growth, urbanization, and settlement in floodplains (Vlachos, 2011). For example, in Côte d'Ivoire (a West African country), the extreme rainfall events of 2014 caused significant material and human damage in Abobo and Attécoubé, highlighting the vulnerability of areas lacking adequate drainage systems (Marcel et al., 2021). Similarly, Ecuador's Manabí province experienced exceptionally high rainfall in 2017, associated with sea surface temperature anomalies in the equatorial Pacific, resulting in adverse social and environmental effects in both urban and rural areas (Pacheco et al., 2019). In recent years, Iran has also experienced cumulative and extreme rainfall events, leading to substantial damage in both urban and rural regions (Yari et al., 2022; Sharafi et al., 2021; Shaikh Baikloo, 2021b; Fazel-Rastgar, 2020; Khoshakhlagh et al., 2014). These events emphasize the need for integrated water management strategies and improved urban planning to mitigate flood risks and their consequences.

### 3.4. Agricultural Impacts

Climate change poses significant risks to agriculture, affecting crop yields and food security. Changes in temperature and precipitation patterns, along with increased extreme weather events, can reduce agricultural productivity, promote pest outbreaks, and alter growing seasons (Lobell et al., 2011; Sudarkodi & Sathyabama, 2011; Prajapati et al., 2024). Addressing these challenges requires adaptation strategies such as the development of climate-resilient crop varieties, improved water management techniques, and advanced early warning systems (Pratap et al., 2024). Sustainable agricultural practices, conservation efforts, and technological innovations play crucial roles in mitigating the impacts of climate change and enhancing resilience in farming communities (Thakur et al., 2024). Collaborative efforts among governments, farmers, researchers, and policymakers are essential to develop and implement effective adaptation measures that ensure food security under changing climatic conditions (Prajapati et al., 2024; Pratap et al., 2024).

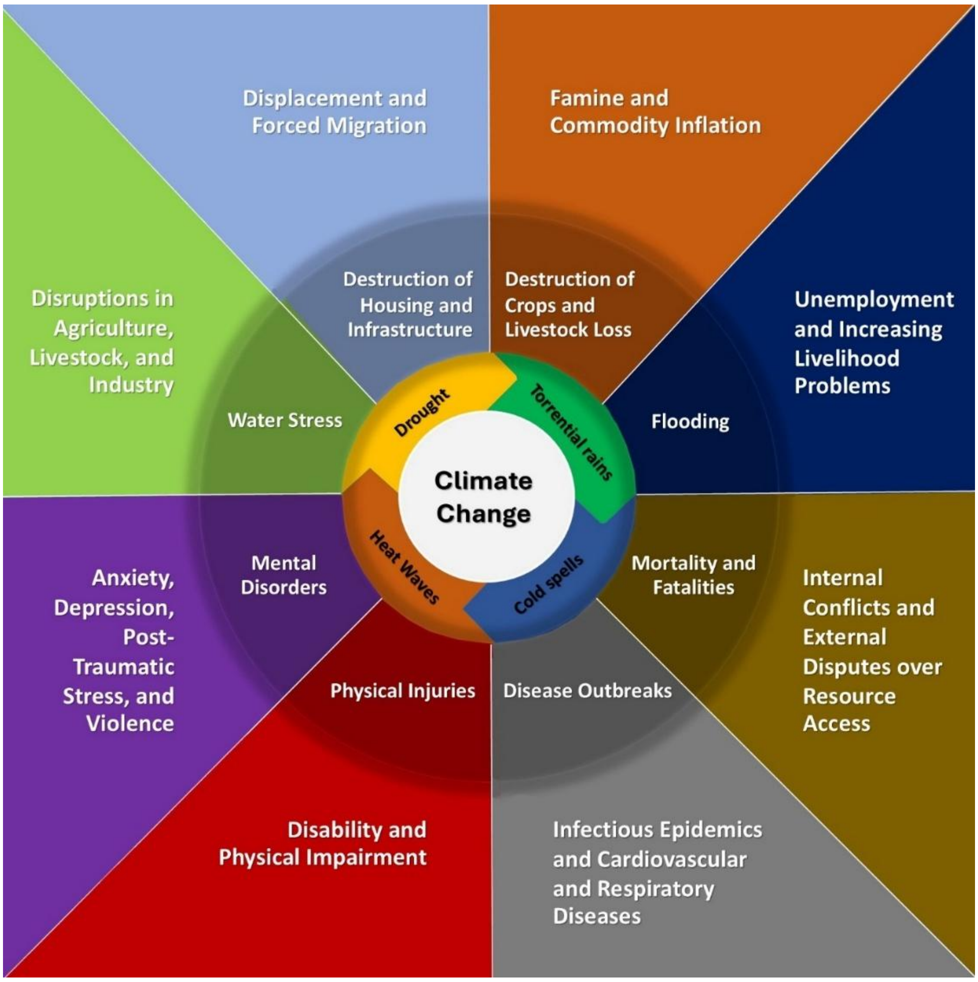


Figure 2. Impacts of increased extreme weather events associated with climate change on human livelihoods and health.

### 3.4.1. Agriculture in Ancient Civilizations

Ancient civilizations in Mesopotamia, Iran, Egypt, and the Indus Valley adapted their agricultural practices to Holocene climatic fluctuations. Early agriculture in northern Mesopotamia relied on rain-fed farming during the Early Holocene (9700–6200 BCE). With declining annual precipitation during the Late Holocene (2200 BCE onwards), communities in southern Mesopotamia developed irrigation technologies to cope with water scarcity (Engel & Brückner, 2021). The Indus civilization, meanwhile, flourished within a unique environmental context characterized by overlapping winter and summer rainfall systems, allowing adaptation to diverse ecosystems (Petrie et al., 2017). These regions, along with Iran, experienced abrupt climatic events such as the 8200, 5200, and 4200-year BP droughts, which severely impacted agricultural production; without adaptation strategies, societal survival would have been compromised (Staubwasser & Weiss, 2006; Shaikh Baikloo, 2020; Shaikh Baikloo & Chaychi, 2020; Shaikh Baikloo et al., 2016). Historically, farmers in arid and semi-arid regions employed various water management techniques—including wells, qanat networks, water storage basins, and drainage systems—to sustain agricultural productivity (Angelakis et al., 2020). These ancient adaptation strategies provide valuable insights for addressing contemporary challenges in irrigated agriculture.

### 3.4.2. Modern Agriculture

Current studies indicate that climate change may significantly reduce the yields of major cereal crops such as wheat and maize by mid-century, threatening global food security (Schlenker & Roberts, 2009). Projections suggest that by 2050, climate change could reduce global maize production by 3–10% and wheat yields in developing countries by 29–34% (Hellin et al., 2012).

Some estimates predict an overall crop yield decline of up to 23% by 2050. Extreme climate events during critical growth periods can substantially affect agricultural output and increase price volatility (Haile et al., 2017). Overall, it is anticipated that by 2050, major cereal production will decline across extensive portions of current arable lands, necessitating adjustments in land-use patterns and crop selection to sustain production growth (Pugh et al., 2016).

### 3.5. Human Health

Climate change poses a significant threat to human health, particularly through its impacts on infectious diseases. Rising temperatures and altered ecosystems exacerbate public health challenges, especially among vulnerable populations (Patz et al., 2005). Shifts in climate patterns can facilitate the spread of vector-borne and waterborne infectious diseases, particularly in developing countries (Shuman, 2010). Climate-related health outcomes are diverse, affecting cardiovascular, respiratory, and gastrointestinal systems, as well as mental health (Kim et al., 2014; Franchini & Mannucci, 2015). Vulnerable groups, including children, the elderly, and those living in poverty, face higher risks (Kim et al., 2014). While some benefits, such as reduced cold-related illnesses, may occur in mid-latitude regions, these are unlikely to offset the overall health risks (Franchini & Mannucci, 2015). Addressing these challenges requires preventive measures, including the development of early warning systems, allocation of resources to raise public awareness about climate change patterns, and promotion of healthy lifestyles (Wu et al., 2016).

#### 3.5.1. Vector-Borne Infectious Diseases

Changes in temperature and precipitation can increase the prevalence of infectious diseases (Fouque & Reeder, 2019). Historical records show that past pandemics, such as the Justinian Plague (6th century CE) and the Black Death (14th century CE), were influenced by climatic conditions (Benedictow, 2004; McMichael, 2012). Global warming—projected to increase Earth's temperature by at least 2 °C by 2100 (Raftery et al., 2017)—could expand the geographic range of diseases such as malaria and dengue fever (Childs et al., 2025). Climatic fluctuations, including El Niño–related events, are associated with outbreaks of infectious diseases across regions (Anyamba et al., 2019). Vector-borne diseases are particularly sensitive to climate change because higher temperatures can increase vector reproduction rates and shorten pathogen incubation periods (Patz et al., 1996; Githeko et al., 2000). These effects are most pronounced in marginal climatic zones and in areas previously free from these diseases (Fouque & Reeder, 2019). While climate change presents future risks, other rapid global changes—such as land-use transformation and urbanization—also significantly affect vector-borne disease dynamics (Sutherst, 2004). Addressing these challenges requires interdisciplinary collaboration and enhanced disease surveillance systems (Patz et al., 1996).

#### 3.5.2. Nutrition and Food Security

Climate change threatens food security, leading to food shortages and related health issues, particularly in vulnerable regions such as South Asia and Sub-Saharan Africa (Lloyd et al., 2011). The World Health Organization estimates that climate change could result in 250,000 additional deaths annually due to malnutrition, heat stress, and climate-sensitive diseases (WHO, 2014).

The impacts of climate change on food systems are multifaceted, affecting soil fertility, nutrient composition in crops, and pest resistance (Owino et al., 2022). These changes can have serious health consequences, primarily by increasing global malnutrition (Baars et al., 2023). Climate hazards such as droughts and floods further destabilize food systems and exacerbate malnutrition (Naheed, 2023). Models predict that climate change could increase moderate stunting by 1–29% and severe stunting by 23–62% in affected regions by 2050 (Lloyd et al., 2011). Addressing these challenges requires sustainable and resilient food systems, climate-smart agriculture, and the preservation of ecosystem services (Owino et al., 2022).

# 4. Paleoclimatology Approaches in Archaeological Studies

## 4.1. The Significance of Paleoclimatology

Paleoclimatology—the scientific study of past climates before the availability of instrumental meteorological records—plays a crucial role not only in environmental, archaeological, and historical research but also in enhancing our understanding of the contemporary climate crisis. By examining paleoclimatic archives such as ice cores, terrestrial and marine sediments, speleothems, and tree rings, researchers are able to reconstruct climatic conditions spanning thousands of years (Jones & Mann, 2004). This perspective enables us to comprehend how ancient societies adapted to climatic fluctuations. Furthermore, paleoclimatic investigations are highly relevant for informing present-day responses to the anthropogenic climate change associated with global warming (Mann et al., 2008).

The application of paleoclimatic research in archaeological studies has increasingly highlighted the importance of climate in shaping human behavior and cultural development. Evidence indicates that past societies responded to environmental stressors within the constraints of their cultural frameworks and available resources—responses that often benefited societal elites (Haldon et al., 2020). Ancient civilizations faced multifaceted challenges, including climate variability, resource scarcity, and social inequality, offering valuable lessons for contemporary societies in domains such as environmental sustainability and political stability (Ahmad, 2023).

Human communities in antiquity exhibited diverse responses to environmental changes, which frequently resulted in social disparities (Robbins Schug et al., 2023). For instance, in the Arabian Peninsula, ancient droughts were associated with population displacements and social transformations, while certain groups maintained resilience through adaptive strategies such as nomadism and effective water management (Petraglia et al., 2020). Similar patterns have been observed in Iran as well (Shaikh Baikloo, 2020). Although the environmental capacities of each region largely determined the subsistence conditions of human populations, the endurance of climatic hardships was unachievable without adaptive strategies.

These studies underscore the complex interplay among climate, environment, and human societies, offering valuable insights for addressing current and future challenges. By integrating archaeological evidence with paleoclimatic data, researchers can investigate how past cultures and civilizations responded to climatic and environmental stressors, thereby providing critical and applicable knowledge for modern societies confronting analogous threats.

## 4.2. Methodologies in Paleoclimate Research

### 4.2.1. Paleoclimate Data

The integration of paleoclimatic data into archaeological research provides critical insights into how ancient societies interacted with their environment (Fig. 3). By reconstructing past climate conditions, researchers can gain a deeper understanding of the contextual factors that influenced human behavior and social development (Mann et al., 2008). Combining multiple proxies, including biological, chemical, and physical remains, enables detailed reconstructions of past environmental conditions (Zarza et al., 2023).

Paleoecology merges archaeological evidence with environmental modeling to offer a comprehensive understanding of past ecosystems and their interactions with human communities (Crabtree, 2023). For instance, a study in the Amazon demonstrated that societies with specialized land-use systems were more vulnerable to climate change, whereas communities practicing multi-cropping agroforestry displayed greater resilience (De Souza et al., 2019). This approach thus provides valuable insights into the cultural responses of ancient and historical societies to climatic events.

### 4.2.2. Sediment Cores

Sediment cores collected from lakes, seas, and oceans are fundamental for reconstructing past climate conditions. Analyses of pollen, diatoms, and isotopic compositions reveal vegetation changes and environmental parameters over time (Bradley, 2015; Adam et al., 1981; Smol & Cumming, 2000). Geochemical proxies, including elemental and isotopic compositions of organic matter, preserve paleoenvironmental information across millions of years of sediment deposition (Meyers, 1994).

These natural archives can be calibrated with modern instrumental data to reconstruct past climates accurately (Kalaivanan, 2017). By analyzing multiple proxies, researchers can track long-term climate changes, assess natural climate variability, and evaluate potential human impacts on climate systems (Smol & Cumming, 2000).

High-resolution dating enhances temporal precision, with commonly used methods including radiocarbon ($^{14}C$), dendrochronology, and luminescence techniques. In Iran, sediment cores from lakes such as Zeribar (Kurdistan), Mirabad (Lorestan), Hashilan (Kermanshah), Neor (Ardabil), Urmia, Parishan, Maharlu, and Arjan (Fars), Kongor (Golestan), and Hamoun (Sistan) have reconstructed over 20,000 years of climate history. Additional studies have been conducted in Jazmurian Playa, Nimbluck dry lake in South Khorasan, and peat bogs near the Jiroft archaeological site (Shaikh Baikloo et al., 2023). Recent high-resolution studies include Hashilan Wetland (Safaierad et al., 2023), Lake Urmia (Sharifi et al., 2023), Lake Neor (Sharifi et al., 2015), and Konar Sandal peat bog in Jiroft (Safaierad et al., 2020).

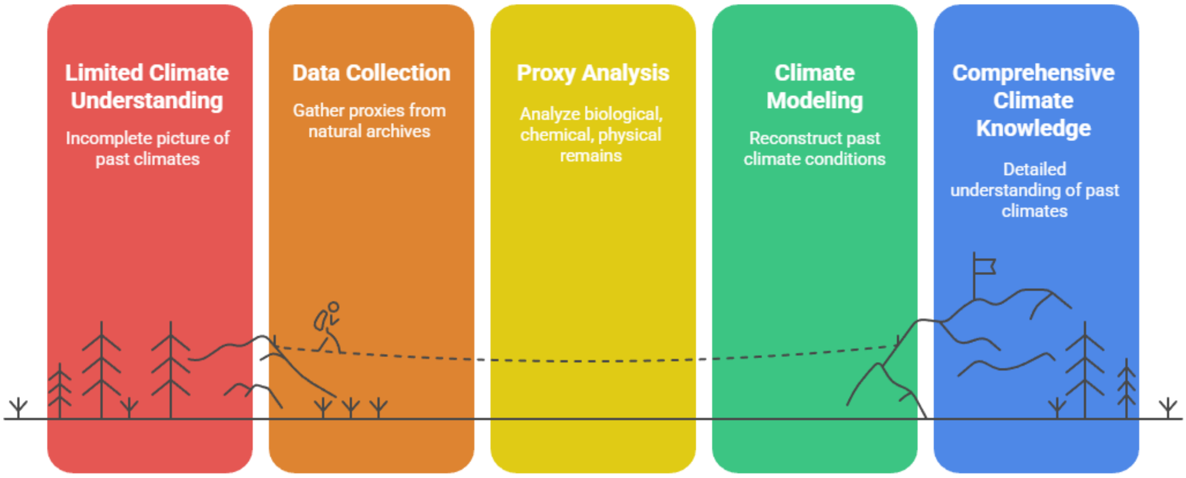


Figure 3. Reconstructing Past Climate.

### 4.2.3. Ice Cores

Glaciers and ice sheets contain trapped gases and isotopes that provide records of past atmospheric conditions and temperatures. Air bubbles in polar ice preserve direct evidence of greenhouse gases such as $CO_2$ and $CH_4$ over hundreds of thousands of years (Banerjee et al., 2022; Bender et al., 1997; Grootes & Stuiver, 1997). Noble gases in these bubbles serve as tracers, revealing past atmospheric composition changes (Winckler & Severinghaus, 2013).

Ice cores provide synchronized records of multiple climate indicators, including temperature, precipitation, atmospheric chemistry, volcanic activity, and solar variability (Óskarsson, 2005). Analyses of trapped gases offer high-resolution insights into changes in atmospheric composition over timescales ranging from decades to hundreds of thousands of years, elucidating the relationship between past climate and greenhouse gas concentrations (Banerjee et al., 2022; Bender et al., 1997).

### 4.2.4. Speleothems

Speleothems (cave formations) are valuable archives of past climate, providing high-resolution records spanning up to 600,000 years (Johnson, 2021). Uranium-series dating techniques allow precise chronological reconstruction (Richards & Dorale, 2003; Wendt et al., 2021). Speleothems preserve climate-sensitive proxies, such as oxygen and carbon isotopes and trace elements, which reveal past precipitation, temperature, atmospheric circulation, and vegetation type (Johnson, 2021; Scheidegger et al., 2008).

Their presence or absence also reflects past environmental conditions, as formation requires sufficient water and soil $CO_2$ (Richards & Dorale, 2003). Speleothem records have significantly advanced understanding of natural climate variability, abrupt climate changes, and monsoon dynamics (Johnson, 2021; Wendt et al., 2021; Fleitmann et al., 2007; Dykoski et al., 2005). Their global distribution and high temporal resolution make them essential for constructing comprehensive paleoclimate databases and informing water resource planning (Scheidegger et al., 2008). In Iran, notable studies include Katalekhor (Zanjan) (Andrews et al., 2020), Qale Kord (Qazvin) (Mehterian et al., 2017), Gol-Zard (North Iran) (Carolin et al., 2019), and Sibaki cave (Southwest Iran) (Soleimani et al., 2023).

### 4.2.5. Tree Rings

Tree-ring studies provide detailed information on past climate and environmental changes over centuries to millennia (Jacoby & D'Arrigo, 1997). Dendroclimatology, a branch of dendrochronology, uses annual tree-ring chronologies to reconstruct past climate conditions (Cook, 2006). Research on Scots pine in Poland identified cold periods and extreme weather events, showing that February–March temperatures consistently influenced tree growth (Koprowski et al., 2010).

Empirical-statistical and process-based modeling methods are used to extract climate signals from tree rings, improving understanding of past climate dynamics (Hughes, 2011). In Europe, dendroclimatic research has reconstructed approximately 10,000 years of climate history (Briffa & Matthews, 2002). In Iran, however, dendroclimatic studies are limited and cover less than 1,000 years of climate records (Arsalani et al., 2021, 2022).

### 4.3. Methodological Advances

Recent technological and methodological advancements have significantly enhanced our understanding of past climate–human interactions. High-resolution climate modeling, combined with advanced dating techniques, now allows for more precise correlations between climatic events and archaeological datasets (Caseldine & Turney, 2010; d'Alpoim d'Alpoim Guedes et al., 2016). Moreover, the integration of multiple proxies, including isotopic analyses, pollen records, and historical archives, enables researchers to develop comprehensive models of past climates and their impacts on human societies (Lotter, 2014). While paleoclimatologists predominantly rely on "natural archives," historical climatologists utilize "societal archives," such as written records (Brönnimann et al., 2018).

Climatic proxies provide critical information on a range of parameters, including temperature, precipitation, and vegetation cover, derived from natural archives (e.g., oceanic and lacustrine sediment cores) as well as archaeological contexts (Patalano & Roberts, 2021). The integration of multiple datasets—spanning paleoenvironmental, archaeological, and documentary sources—facilitates the exploration of complex climate–human–environment interactions and the assessment of socio-ecological resilience. To achieve a comprehensive understanding of Earth system changes, precise reconstructions of past climate, human activity, and their interactions across all temporal and spatial scales, alongside the development of long-term simulation models, are essential (Dearing, 2006).

## 5. Conclusion

The synthesis of paleoclimatic data with archaeological evidence provides a powerful framework for understanding the complex interactions between climate and human societies. Ancient communities often employed diverse adaptive strategies, including sophisticated water management technologies, to buffer against climate variability and environmental stress.

Consequently, archaeology offers valuable insights into how past cultures and civilizations adapted to environmental challenges. In the context of unprecedented contemporary climate change driven by global warming, lessons drawn from the past can inform policy-making, resource management, and community efforts aimed at developing adaptive strategies and enhancing resilience, ultimately contributing to increased sustainability and socio-ecological robustness.

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