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TOPICAL REVIEW

The history of climate and society: a review of the influence of climate change on the human past

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Abstract

Recent decades have seen the rapid expansion of scholarship that identifies societal responses to past climatic fluctuations. This fast-changing scholarship, which was recently synthesized as the History of Climate and Society (HCS), is today undertaken primary by archaeologists, economists, geneticists, geographers, historians and paleoclimatologists. This review is the first to consider how scholars in all of these disciplines approach HCS studies. It begins by explaining how climatic changes and anomalies are reconstructed by paleoclimatologists and historical climatologists. It then provides a broad overview of major changes and anomalies over the 300,000-year history of Homo sapiens, explaining both the causes and environmental consequences of these fluctuations. Next, it introduces the sources, methods, and models employed by scholars in major HCS disciplines. It continues by describing the debates, themes, and findings of HCS scholarship in its major disciplines, and then outlines the potential of transdisciplinary, 'consilient' approaches to the field. It concludes by explaining how HCS studies can inform policy and activism that confronts anthropogenic global warming.

1. Introduction

The idea that changes in climate influenced human history can be traced back to antiquity (Glacken 1973). Few sought physical evidence for these changes until the seventeenth century, when some scholars began to interpret marine fossils and erratic boulders as relics of ancient, radically different climates, while others started to identify fluctuations in the output of the Sun and other stars (Tassoul and Tassoul 2004, Tierney *et al* 2020a). Many European intellectuals argued that climate—a condition they defined as synonymous with latitude or local air quality—determined human physical, mental, and moral characteristics (Livingstone 1991, Fleming 1998). It was an assumption they used to justify colonial conquest—and it implied that a gradual change in climate could alter the fortunes of civilizations (Zilberstein 2016, Warde 2018). In the nineteenth century, scientists in newly professionalized disciplines began to speculate that these changes could unfold on human timescales. Their motivations included a growing awareness of solar variability; new efforts to monitor and exploit colonized landscapes; and, in the Austro-Hungarian Empire, a unique quest to legitimize empire by uncovering how atmospheric circulation connected otherwise isolated populations. (Coen 2018, Heymann and Achermann 2018, Mauelshagen 2018, Morgan 2018).

In the closing decades of the century, astronomer A. E. Douglass realized that variations in the width of growth rings in trees could serve as proxies for seasonal precipitation (1914). By then, some economists and geographers had started to

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look for statistical relationships between trends in grain prices, weather, and hypothesized causes for weather (such as sunspots) (Jevons 1875, Brückner 1895). With their controversial studies as inspiration, geographer Ellsworth Huntington used the assumption that an ideal climate existed for civilization to argue that century-scale changes in climate, identified by Douglass in tree rings, had enabled the rise and triggered the downfall of past societies (Huntington 1913a, 1917a, 1917b). Meanwhile, oceanographer Otto Pettersson concluded that climatic changes—determined, he thought, by the position of the Moon and Sun relative to Earth—had shaped the history of Norse settlements in fifteenth-century Greenland and Iceland (Pettersson 1914, Utterström 1955). These claims eventually spurred the development in distinct regional research cultures of new, radically interdisciplinary fields of study that gradually grew in sophistication and were recently synthesized as the History of Climate and Society, or HCS (McCormick 2019, Storozum et al 2019, Degroot et al 2021).

HCS may be defined as the study of human responses to trends, anomalies, and regular variability in past climate. It is a fast-growing field that is today undertaken primarily by archaeologists, economists, geneticists, geographers, historians and paleoclimatologists (Degroot et al 2021). Here, we provide the first survey of the field as it is practiced in all of these disciplines, and as it considers the entire, approximately 300 000 year history of anatomically modern humans. Since HCS depends on accurately identifying past climatic changes, we begin by explaining how these changes are identified, or 'reconstructed', by paleoclimatologists and historical climatologists. We provide a broad overview of what reconstructions reveal about how climate changed over the past 300 000 years. We then introduce the distinct evidence, methods, and models used by scholars in major HCS disciplines. We identify key findings and themes in each discipline, by selecting what we consider particularly influential or representative case studies. We describe the potential of transdisciplinary, 'consilient' approaches to HCS scholarship (Lang et al 2012), and conclude by explaining how HCS scholarship may inform efforts to cope with today's global warming.

2. Reconstructing climate change

For the period before the late nineteenth century, when colonial states established weather stations with reliable meteorological instruments across their growing territories, our knowledge of past climate comes primarily from proxy data in the archives of nature. Examples of proxy records include the annual rings of trees, the geochemistry of cave formations and coral skeletons, the composition and contents of polar and high-altitude glaciers and ice sheets, and the organic and inorganic components of lake and ocean sediments (figure 1) (Baumgartner et al 1989, Jones et al 2009, Bradley 2014, Kaufman et al 2020b).

Proxy records from these archives are the result of biological, chemical, and physical processes by which organisms or systems sense the variability of their environment and record it in a material archive whose characteristics we can observe and measure (Evans et al 2013). Paleoclimatologists typically reconstruct past climate from these data by inverting this chain of processes, either quantitatively or qualitatively. To that end, they use measurements of the proxy system and an understanding of how it reflects its past environment to estimate the conditions under which it formed. This inverse process of paleoclimate reconstruction is often imperfect, however, necessarily making inference from our modern observations of the proxy toward the past environment without complete knowledge or representation of how the archive was formed and how accurately or uniquely the sensor recorded the climate signal of interest (Hughes and Ammann 2009, Inkpen and Wilson 2009, Tingley et al 2012, Evans et al 2013).

Past climate reconstructions may be relative and qualitative—classifying periods as wetter or drier, for example, and warmer or colder—based on a mechanistic or physical understanding of the proxy. Alternatively, reconstructions can be absolute and quantitative, with the proxy data measurements transformed statistically into climate metrics like temperature, precipitation, soil moisture, salinity, or features of the large-scale ocean or atmosphere circulation (Hughes and Ammann 2009, Tingley et al 2012, Hu et al 2017). Where proxy records overlap directly with instrumental observations, statistical estimates of past climate can be directly calibrated in time and validated on a portion of withheld instrumental data. In those cases where proxy records are either too low resolution (each measurement reflecting decades or centuries) or where the chronology is too uncertain (the time of formation constrained with decades or longer), statistical transfer functions using a space-for-time calibration can be used to estimate climate variables from the proxy measurements (Birks et al 2010, Juggins and Birks 2012). Chronology is critical, as it provides evidence for the sequence of events and therefore is a prerequisite (although not sufficient) for determining both physical or social causality.

Every paleoclimate reconstruction comes with uncertainties caused by the imperfect reflection of climate variability by the proxy system; the assumptions and methods used to estimate past climate from natural archives; and the limits of chronological precision. Each type of proxy record has distinct advantages and limitations. For instance, tree-ring records are well-replicated and provide exact annual chronology and so can be calibrated directly against the overlapping instrumental record; however, they are largely limited in their length to the last millennium or less and most of these records

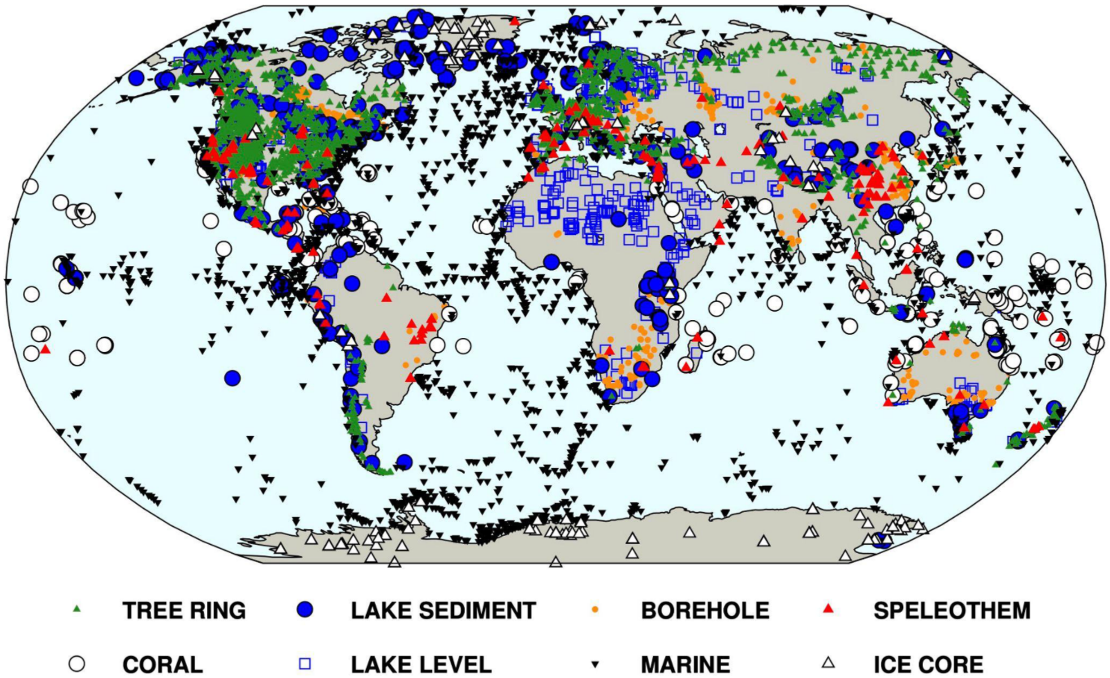


Figure 1. Spatial distribution of paleoclimate and paleoenvironmental data for major proxy data types archived at the NOAA World Data Center for Paleoclimatology (data served from www.ncei.noaa.gov/products/paleoclimatology on 1 March 2022). As discussed in detail in the text, each proxy type has advantages and disadvantages for reconstructing past climate with respect to human history. In particular, low temporal resolution and chronological uncertainties may limit a proxy's applicability when assessing the link between specific events in human history and climate extremes, even though they can provide information on climate change and variability on centennial or longer timescales relevant to longer-term cultural change and human evolution.

are from Northern Hemisphere terrestrial regions (George 2014, Anchukaitis and Smerdon 2022). Marine sediment records provide much longer records of past climate, potentially many millions of years, but are usually lower resolution (centuries to millennia), time-uncertain (by hundreds of years), and biased toward coastal marine environments.

Climate changes have provoked responses in human material culture that provide additional proxies for climate reconstruction, in what historical climatologists call the 'archives of societies.' These archives include either observations of past weather, usually as recorded in surviving textual evidence, or evidence of activities that must have been profoundly influenced by weather, such as autumn harvests or the use of canals in winter. Sometimes they are both: logbooks written to aid navigation in the age of sail, for example, include both wind or sea ice measurements, and descriptions of marine activities that reacted to the velocity and direction of wind or the thickness and distribution of sea ice (García-Herrera *et al* 2005, García-Herrera *et al* 2018, Degroot 2020, Degroot and Ottens 2021). It can be easy to confuse one kind of source with another; artistic depictions of extreme weather could be weather observations, for example, but more commonly were created through actions only indirectly influenced by weather (Brönnimann *et al* 2018, Pfister 2018).

The archives of society should also be considered with appropriate skepticism. Textual evidence for past weather should never be taken at face value, since observers usually had many motivations for recording weather and often limited means of measuring weather. Such evidence can be discontinuous unless archived by institutions, and typically focuses on weather extremes rather than averages. Records of activities influenced by weather should similarly be used with caution, since those actions were inevitably affected by many other forces. Historical climatologists accordingly use index systems to quantify and standardize their qualitative information on simple ordinal scales that can sometimes be calibrated to modern instrumental measurements. Reconstructions created with index systems can reveal climatic trends with uniquely high resolution, for places, times, or seasons that may be difficult or impossible to cover using the archives of nature (Brázdil *et al* 2005, Blöschl *et al* 2020, Nash *et al* 2021).

3. Climatic changes and causes in *Homo sapien* history

On multi-millennial timescales, climate change over the 300 000 year history of anatomically modern humans was paced by the changes in the Earth's orbit, which control how incoming solar energy (insolation) is distributed latitudinally across the planet and over the seasonal cycle. These orbital cycles include eccentricity (how elliptical the Earth's orbit is, a 100 000 year cycle), obliquity (changes in the tilt of the planet, a 41 000 year cycle) and precession (the timing of perihelion in the seasonal cycle, a 23 000 year

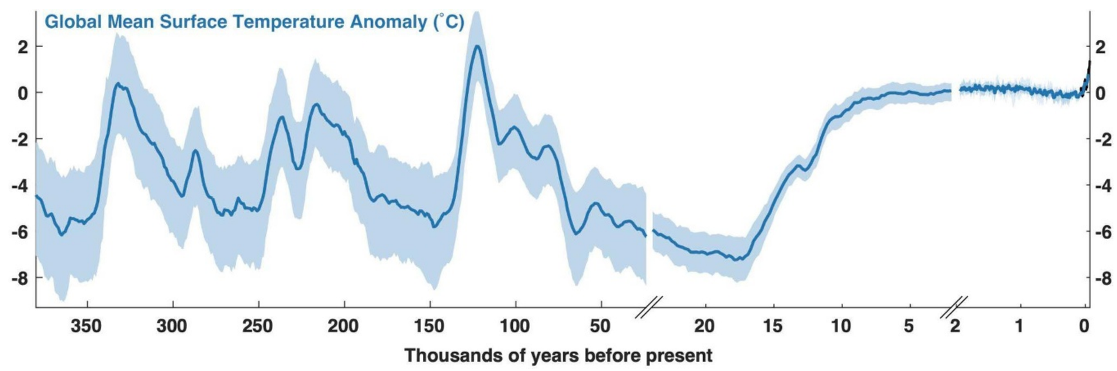


Figure 2. Global mean surface temperature changes for the past ca. 350 000 years. The curve is a composite of three reconstructions: (1) Snyder (2016) between 350 000 and 24 000 years; (2) Osman *et al* (2021) between 24 000 and 2000 years, (3) a composite estimate of temperature for the last 2000 years (the Common Era) from the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) compilation (Masson-Delmotte *et al* 2013) and more recent reconstructions by Stoffel *et al* (2015), Schneider *et al* (2015), Wilson *et al* (2016), Guillet *et al* (2017), Anchukaitis *et al* (2017) and the PAGES 2k Consortium (2019). Temperatures are shown relative to the estimated mean of the preindustrial period. Uncertainties prior to the Common Era are those estimated in the original publications. Uncertainty in the composite of the last 2000 years is based on the full temperature range of the 21 reconstructions included in the composite.

cycle). By changing the seasonal amount of insolation in the high latitudes, these cycles, combined with ice-albedo feedbacks and changes in greenhouse gasses (Ruddiman 2006) drove three rounds of expansion and melting of the high latitude ice sheets in the last 300 000 years (figure 2). Feedback is an essential concept in climate scholarship; it refers to the outcome of a change that either amplifies (a positive feedback) or mutes (a negative feedback) the initial change. A positive feedback magnifies changes in the Earth system such that a small initial change results in an outsized outcome.

During glacial periods, global temperature was perhaps 6 °C colder than preindustrial conditions (Snyder 2016) (figure 2). Large ice sheets covered northern North America and Eurasia, leading to a drop in global sea level of around 120 m (Waelbroeck *et al* 2002). This sea level change exposed the Bering Strait land bridge, connected the British Isles and southern Scandinavian islands via a dry North Sea region known as Doggerland, and revealed shallow shelves in the tropics. In the Indonesian region, the emergence of the Sunda and Sahul shelves shifted the patterns of tropical rainfall, resulting in extreme drying (Windler *et al* 2019). Overall, global climate was drier (Bartlein *et al* 2011), since a cold atmosphere holds less water. However, there were regional exceptions. The southwest region of North America was much wetter, for example, as the Laurentide ice sheet deflected winter storms farther south (Oster *et al* 2015). Likewise, not all places on Earth were colder during glacial periods. Beringia (present-day Alaska and northeastern Siberia) experienced minimal cooling (Bartlein *et al* 2011, Tierney *et al* 2020b) and remained unglaciated (Glushkova 2001) because the ice sheet caused a change in atmospheric circulation that made the region warmer and drier (Löfverström and Liakka 2016).

On millennial timescales, the Northern Hemisphere experienced a number of rapid fluctuations in temperature during the last glacial period, known as Heinrich Events (1988) and Dansgaard–Oeschger events (Johnsen *et al* 1992). Within a matter of years, temperatures over Greenland changed by more than 10 °C during these events, and these changes endured for more than a millennium (Johnsen *et al* 2001). There is evidence that such events influenced climate not only in the high latitudes but also in the tropics, where they are associated with weaker Indian-Asian monsoon rains (Wang *et al* 2001).

During interglacial warm periods, global temperature was similar to, or perhaps slightly higher than, pre-industrial (that is, late nineteenth-century) conditions (Snyder 2016). Northern Hemisphere summer temperatures, however, were 3 °C–5 °C warmer (Otto-Bliesner *et al* 2021), leading to partial melting of the Greenland ice sheet and 6–9 m of sea level rise (relative to pre-industrial time; Kopp *et al* 2009). A defining characteristic of interglacial periods is an intensification and expansion of the African and Asian monsoon systems (Otto-Bliesner *et al* 2021). For example, during the Last Interglacial, the African monsoon system expanded deep into the Sahara Desert (Drake *et al* 2011) and possibly as far as the Levant region in the eastern Mediterranean (Drake *et al* 2011, Torfstein *et al* 2015, Tierney *et al* 2017a).

The Last Glacial Maximum (LGM) peaked at about 20 000 BP ('before present,' a radiocarbon dating convention meaning years before 1950). Thereafter, global temperatures rose approximately 7 °C, an increase paused only temporarily by the Younger Dryas event, the last millennial-scale climate perturbation (Alley 2000, Osman *et al* 2021) (figure 2). As with previous glacial cycles, this deglacial warming was triggered by orbital forcing, but the direct radiative drivers were the rise in greenhouse gasses (carbon dioxide and methane) and the loss of the Northern Hemisphere ice sheets. In the wake of the Younger Dryas, the Pleistocene geological epoch (2580 000–11 700 BP) distinguished by alternating glacial and interglacial periods, gave way to the Holocene epoch (11 700 years BP to pre-industrial), the current interglacial period. The Laurentide ice sheet, which once covered a large portion of North America, lasted until about 7500 years ago (Peltier *et al* 2015). Shortly before its demise, a rapid cooling of approximately 6 °C occurred over Greenland at 8200 BP (Thomas *et al* 2007). This '8.2-kiloyear event' is seen in Northern Hemisphere climate records, and also may be associated with a 1000 year long drying period in Northern Africa (Rohling and Pälike 2005, Morrill *et al* 2013, Tierney *et al* 2017b).

From about 7000 years ago to the twentieth century, global mean annual temperatures were comparatively stable (figure 2), even if temperatures evolved differently at local to regional scales and for specific seasons. Reconstructions of the Holocene global temperature changes showed a 'Holocene Thermal Maximum' at around 6–7000 BP (Marcott *et al* 2013, Marsicek *et al* 2018, Kaufman *et al* 2020a). However, the recent reconstruction of Osman *et al* (2021) does not show this feature, and there is an ongoing debate about whether the Holocene Thermal Maximum is an artifact of spatial bias (Osman *et al* 2021) or reflects a seasonal (summer) signal (Bova *et al* 2021, Wanner 2021).

In either case, while global mean annual temperatures were fairly stable through the Holocene, this period saw large shifts in the hydrological cycle (Mayewski *et al* 2004). In the early Holocene (11 000–5000 BP) the African monsoon intensified once again, resulting in an expansion of grasslands, shrubs, and perennial lakes into the Sahara Desert (DeMenocal and Tierney 2012). Monsoonal rainfall also intensified in India; meanwhile, the South American monsoon was much weaker (Brierley *et al* 2020). In the Mediterranean and parts of Asia there is speleothem evidence for a period of intense drying during a '4.2-kiloyear event' (beginning in 4200 BP) that, despite its name, differed greatly from the 8.2-kiloyear event (Carolin *et al* 2019).

Enhanced spatial coverage and improved temporal resolution allow for detailed paleoclimate reconstructions of the late Holocene and the Common Era (CE, from the year 1 to the present) using tree-rings, corals, ice cores, speleothems, sediment records, and other proxies with sufficient temporal resolution (Frank *et al* 2010, PAGES2k 2013, Smerdon and Pollack 2016, Emile-Geay *et al* 2017, Esper *et al* 2018, PAGES 2k Consortium 2019, Anchukaitis and Smerdon 2022). Prior to the onset of modern anthropogenic warming, temperature reconstructions spanning the last 2000 years reflect a mix of forced and internal variability across a range of time scales, from interannual to millennial, including the seasonally and spatially variable influences of orbital forcing (Esper *et al* 2012, Lücke *et al* 2021).

The most important Late Holocene forcing prior to the Industrial Revolution came from explosive volcanic eruptions, which can reduce incoming shortwave solar radiation by injecting sulfate aerosols into the stratosphere, cooling surface temperatures, altering the hydrological cycle, and affecting ocean and atmospheric circulation (Timmreck 2012, McGregor *et al* 2015, Esper *et al* 2018). Temperature reconstructions show periods of widespread decadal-scale cooling linked to explosive volcanism in the 6th, 15th, 17th, and 19th centuries in particular. Forcing from volcanic eruptions was the most important contributor to initiating and sustaining the 'Little Ice Age' (LIA), which paleoclimatologists date from the 14th through mid-19th centuries (Robock 1979, Crowley 2000, Zhong *et al* 2011, Esper *et al* 2018, Slawinska and Robock 2018, Anchukaitis *et al* 2019, Brönnimann *et al* 2019) as well as the 'Late Antique Little Ice Age' (LALIA), a period of uncertain spatial and temporal extent that began with two large eruptions in 536 and 540 CE (Gunn 2000, Larsen *et al* 2008, Churakova *et al* 2014, Sigl *et al* 2015, Büntgen *et al* 2016, Toohey *et al* 2016, Newfield 2018). Helama *et al* (2017a) suggested that the LALIA was embedded within a somewhat longer but ambiguously dated 'Dark Ages Cold Period' (DACP), spanning from approximately 400–765 CE.

Solar variability is now widely thought to play a minor role in climate fluctuations over the Common Era (Schurer *et al* 2014), yet the mechanisms for and significance of solar influences on climate remain uncertain across a range of spatial and temporal scales (Gray *et al* 2010, Lockwood 2012). Cold summer temperature anomalies did coincide with Grand Solar Minima in the 14th, 16th, and 17th centuries (Anchukaitis *et al* 2017). Even during century-scale events, however, internal climate system variability (which arises naturally without changes in planetary energy balance from the complex interaction of oceans and atmosphere) and earth system feedbacks were very important contributors to the temporal evolution of cooling; the spatial patterns of temperature anomalies; and interannual-to-multidecadal climate variability at the local and regional scale (Goosse *et al* 2005, Jungclaus *et al* 2010, Fernández-Donado *et al* 2013, Lehner *et al* 2013, Schleussner and Feulner 2013, Helama *et al* 2017b, Anchukaitis *et al* 2019, Neukom *et al* 2019).

The Medieval Climate Anomaly (MCA; *sensu lato* 800–1300 CE), a period of relatively warm temperatures spanning the first and second millennia of the Common Era, likely reflects a combination of a weak increase in radiative forcing and internal climate system variability (Goosse *et al* 2005, 2012, Fernández-Donado *et al* 2013). In particular, spatial climate reconstructions of medieval temperatures suggest internal variability played a strong role in determining the magnitude and regional timing of temperature maxima (Goosse *et al* 2005, Diaz *et al* 2011, Neukom *et al* 2019). Indeed while it is therefore possible to roughly identify periods of the Common Era corresponding to large- and centennial-scale temperature anomalies, such as the MCA, LIA, and LALIA, at the local to regional scale, and from interannual to decadal periods, internal variability would have played a very important role in the temperature anomalies experienced by human societies (Degroot *et al* 2021).

Internal variability played an even greater role for precipitation and soil moisture anomalies, which also had impacts on agricultural productivity. Proxy reconstructions show spatial and temporal variability in past hydroclimate dominated by the influence of internal variability, including large-scale modes of ocean-atmosphere like the El Nino Southern Oscillation (ENSO) (Cook *et al* 2010a, 2010b, 2011, 2014, 2018, Hunt 2011, Ault *et al* 2013, Tierney *et al* 2013, Ummenhofer *et al* 2013, Coats *et al* 2015, 2016, Stevenson *et al* 2015, PAGES Hydro2k Consortium 2017). Ultimately, analyses that assume that uniform, widespread, or persistent warm and cold, or wet and dry conditions persisted during amorphous climate periods like the LIA are seldom justified when examining the spatial and temporal scales of interactions that exist between climate and human society (Degroot *et al* 2021).

4. Uncovering human responses: evidence

Evidence for human responses to these climatic changes survives in everything from the genes and languages of present-day populations, to the ruins, trash heaps, archived documents, and art of ancient societies. HCS scholarship requires many disciplines primarily because this evidence is so diverse and so abundant.

Past demographic events (such as population bottlenecks and migrations) and episodes of natural selection for genetic variants (in for example genes for disease resistance or high metabolism), left signatures in the genetic makeup of contemporary populations. Because climates transformed local environments and thereby influenced how human populations could inhabit them, the DNA of contemporary individuals can suggest compelling links between human and climatic histories. Large databases of genetic markers have been assembled for studies of demography and selection, with much of the data being publicly available (e.g. The 1000 Genomes Project Consortium 2015). However, the large amount of information that can be gleaned from genomes, including inferences about health conditions, has raised a number of ethical issues of consent (Caulfield and Murdoch 2017). Current practices accordingly require full involvement with communities that donate genetic material to make sure that all participants are properly informed and involved in research (Claw *et al* 2018).

Over the last two decades, the development of techniques to extract DNA from ancient remains (such as bones and hair) has revolutionized our ability to reconstruct human history. It is now possible to build time series that directly record the progressive accumulation of genetic signatures from past events (Orlando *et al* 2021). However, preservation of ancient DNA is greatly dependent on environmental conditions. The permafrost has yielded DNA from hundreds of thousands of years ago (van der Valk *et al* 2021), but recovering DNA from the tropics is very challenging even when dealing with much shorter time horizons (Orlando *et al* 2021). Recent developments in techniques that recover DNA from sediment have further opened the possibility of building detailed time series of site occupation (Crump 2021), although fragmented material recovered in this way is not amenable to complex population genetic analysis (Sigsgaard *et al* 2020).

The archaeological record affords a wide variety of sources for the study of past interactions between environments and human societies. Most fundamentally, archaeological data in the form of diachronically and spatially structured site distributions can be used to relate human settlement to broad ecological parameters, and to changes in those parameters. At the core of archaeology is material culture, much of which can be understood as 'extra-somatic means of adaptation' (Binford 1962). Changing forms of hunting equipment, farming or herding practices, mobility, and political arrangements can be read from the archaeological record directly (Evans 2002, Hussain and Riede 2020).

In addition, archaeological excavations commonly yield not only human-made artifacts but also many 'ecofacts,' or 'geofacts.' These include plant and animal remains, soils, and bio- or geoarchaeological substances that require laboratory analysis. These substances are by no means limited to DNA, and include lipids, isotopes, and other residues that are interpreted by specialists in, for example, environmental archaeology, geoarchaeology, archaeozoology, and palaeoethnobotany (Clift *et al* 2011, Sandweiss and Kelley 2012, Murphy and Fuller 2017). Increasingly, archaeological sources provide a bridge between evidence in history and genetics.

Climate historians, along with many geographers and economists, primarily rely on written accounts of the past. Accordingly, their studies have long focused on times and places that are well documented by surviving textual evidence. To be useful for climate historians, such evidence must either mention weather directly, or describe environmental and social changes clearly influenced by weather. Documents may suggest interactions between climatic and social changes on very different scales. Diaries and correspondence, for example, may reveal the lived experience of weather and associated ecological phenomena, such as plant and animal phenology, while accounts archived by institutions and governments can record the shifting fortunes of entire societies or economic sectors confronted with climate change (Huhtamaa and Helama 2017a, García-Herrera *et al* 2018, White *et al* 2018b, Van Bavel *et al* 2019, Degroot 2020, Pfister and Wanner 2021).

Some sources interrogated by climate historians register human and environmental changes across many scales in time and place. Visual art, for instance, may depict discrete, local events—skaters on a cold winter's day, for example—while using pigments and appealing to regional markets in ways that registered decadal economic trends, and while depicting cultural values, ideas, or artifacts that took centuries to develop (Behringer 2010, Ray 2019). Climate historians work to identify the influence of weather and climate across different resolutions, especially when combining source types, and to isolate the effects of weather from those of cultural, political and socioeconomic forces (Bell and Ogilvie 1978, Chiari 2019, Van Bavel *et al* 2019, Williamson 2020).

Although the textual record useful for historians can seem overwhelmingly vast, documentary evidence is in fact unavailable for much of the globe before the eighteenth century (Brönnimann and Wintzer 2019). In regions and periods where textual sources are sparse or nonexistent, historians are beginning to employ historical linguistic data to understand human responses to past climate change (De Luna 2016, Hannaford and Nash 2016, Degroot *et al* 2021). Historians may also use oral histories to identify environmental changes, often at relatively low resolution but occasionally across centuries or even millennia (Cruikshank 2001, 2007). Still, the limitations of historical sources across large scales in time and space today encourage collaboration between historians and scholars in other disciplines, particularly archaeology and paleoclimatology.

5. Uncovering human responses: methods

Population genetics provides tools both to reconstruct past demography and thereby to quantify human responses to climate change, and to study specific genes that underpin selective responses to climate. The techniques used for these purposes depend on the nature of the data available. For demographic reconstructions, earlier studies mostly relied on mitochondrial DNA (mtDNA). The small size of the mitochondrial genome and its haploid nature make it an easy target for sequencing, both in contemporary and ancient samples. However, the power of demographic reconstructions based on mtDNA is limited, since mtDNA is a single, non-recombining marker. While it is easy to model its inheritance, the genealogy of a single marker is highly stochastic and can be poorly representative of underlying demographic history (Balloux 2010). Nuclear markers can provide much greater power, but the large size of the nuclear genome meant that, until a decade ago, it was prohibitive to build extensive datasets of complete genomes.

Single nucleotide polymorphism (SNP) chips, which genotype pre-defined positions of the genome known to be variable, have been used extensively to quantify human population structure. A challenge when using SNP chips is that the process of choosing the positions of interest (known as 'ascertainment') is biased towards variants more common in the discovery panel (the group of individuals used to choose the SNPs), and towards variants with intermediate frequencies (as rare markers are unlikely to be present in the small discovery panel) (Nielsen 2004). This ascertainment bias prevents the use of many demographic modeling techniques that rely on unbiased estimates of variant frequencies (Nielsen 2004, Albrechtsen *et al* 2010). Geneticists once used microsatellites—repetitive regions in the genome—as markers for population genetics analyses. However, modeling their evolution is challenging, and these markers have fallen out of fashion as they are not cost effective.

Given the sharp drop in the cost of sequencing over the last decade, whole genome sequencing has become the standard approach, with projects building datasets of hundreds or even thousands of genomes (The 1000 Genomes Project Consortium *et al* 2015). Yet geneticists studying ancient material with scarce, damaged, or fragmented DNA may have difficulty choosing which genetic markers to focus on (Orlando *et al* 2021). Shotgun sequencing of the whole genome is possible, but expensive as much of the DNA found in ancient remains originated in microbes—rather than humans—and is therefore not relevant to most HCS studies. Targeted capture uses the same logic as SNP chips and focuses on specific positions (Orlando *et al* 2021), but the ascertain bias that results from concentrating on these positions means that the data produced by this method can only be used for certain types of analysis.

Archaeologists have also developed an extensive toolbox for approaching human-environment relations. As accurate chronologies are essential in virtually any such attempt, dating methods and the downstream statistical treatment of dating information has received much attention. Complementing chronology, archaeologists have long used Geographic Information Systems (GIS) to aid their analysis of distribution data. The integration of digital methods into environmental archaeological analyses is increasingly seamless, and offers useful points of contact with neighboring disciplines such as geography (Siart *et al* 2017). A similar form of methodological fellowship aligns environmental and geoarchaeology with the biological and geological sciences respectively (Pollard 1999). Basic and advanced field and laboratory techniques developed in the former can often

	Cause-of-Effect	Effect-of-Cause
Evidence	Includes qualitative evidence in diaries, correspondence, art, etc.	Only quantitative or quantifiable evidence
Interpretation	Primary sources typically evaluated and contextualized	Primary sources often taken at face value, or not considered at all
Methods	Inferences, counter-factuals, comparisons with similar cases	Identification of statistically significant correlations, statistical causality tests
Scope	Decade- or annual-scale case studies, compiled in century-scale surveys	Some decade-scale studies, more often century or millenial scale
Interpretation of Causation	Climate change as a necessary and sufficient condition for social changes in specific case studies	Climate change as a cause of social change; not necessary or sufficient in all instances of that social change

Figure 3. Different methods and sources used in HCS scholarship. Scholars may use both methods in the same publication, but more commonly, only one method is used (White and Pei 2020).

be transferred to the specific study of anthropogenic soils and biological samples deriving from archaeological contexts.

Archaeology's grounding in fieldwork allows for the study of human responses to climate change across a range of spatiotemporal scales. Occasionally, a single site will yield evocative evidence of abandonment or adaptation. At other times, such responses will be more clearly visible in the large-scale patterns emerging from inter-site comparisons. Like many scientific disciplines, archaeology is experiencing a rapid shift towards computational methods and working with large quantities of data. The often-fragmentary nature of archaeological evidence and the variable granularity of the archaeological record sometimes poses challenges. However, on both epistemological (Currie 2018) and practical (Caseldine and Turney 2010, Izdebski *et al* 2016, Boivin and Crowther 2021) grounds there are good reasons to believe that assessments of past human-environment relations based on archaeological materials are becoming increasingly robust.

In general, climate historians employ the same techniques of source analysis and criticism that are followed by most other historians. To use these techniques, historians study the historical contexts in which sources were produced; learn the methods by which sources communicated information (in the case of textual sources, often through training in languages or paleography); and then identify sources in repositories (for textual sources, in archives or libraries through consultation with archivists and librarians). In order to ascertain the legitimacy and authenticity of these sources as evidence useful for confirming or rejecting historical hypotheses, climate historians identify which individuals or institutions were responsible for them, and when, where, how, and with what purpose they were created (Howell and Prevenier 2001, Berkhofer 2008). The historical method can discourage climate historians from assuming that historical sources provide reliable and transparent accounts of weather, or activities influenced by weather, which in turn can discourage them from making spurious connections between human and climatic histories. Scholars in other disciplines who make use of historical primary sources—including geographers and economists—may use historians' interpretations of these sources without realizing that those interpretations are not universally agreed upon by historians (Van Bavel *et al* 2019).

Most HCS scholars who use historical sources employ one of two broad methods for establishing that climatic changes caused or helped cause societal changes (figure 3). Historians largely follow what White and Pei have recently coined the cause-of-effect method by deriving inferences from close textual analysis and contextualization; comparing outcomes in similar cases of social or climatic change; and considering counterfactual scenarios. These longstanding elements of the historian's toolkit are used by climate historians to develop narratives that establish climatic changes or anomalies as both necessary and sufficient conditions in particular instances of social change (White and Pei 2020). Geographers and economists, by contrast, largely use an effect-of-cause method by quantifying historical evidence and finding correlations between climatic and social trends

(De Vries 1980, White and Pei 2020). Significant correlations, interpreted at times using statistical methods for identifying causation, can ostensibly reveal the control of the climate variable over diverse social variables (Zhang *et al* 2010, Brunt 2015, Huhtamaa and Helama 2017b). For geographers and economists, this method establishes climate change as a cause of different forms of social change, without being necessary or sufficient in all instances of that social change (White and Pei 2020).

These different ways of establishing causation are, in principle, mutually compatible. Yet in practice geographers and economists have criticized the cause-of-effect method as being insufficiently rigorous or 'scientific,' and too limited to specific case studies that lack predictive power. At the same time many historians have dismissed the effect-of-cause method as insufficiently grounded in textual analysis, and lacking interpretive power in contingent historical case studies (Degroot 2018a, Zhang *et al* 2019). Subdivisions also persist between scholars using each method. While some historians employing the cause-of-effect method, for example, conclude that modest climate changes definitely transformed past societies, others focus on smaller scales of analysis, and emphasize uncertainties that follow from gaps in surviving evidence. Some use probabilistic terminology to identify connections between climatic and social processes unfolding across different scales in time and space (Degroot 2018c).

Recently, scholars have identified systematic shortcomings in how many HCS studies have used both cause-of-effect and effect-of-cause methods. HCS studies using either method have, for example, misinterpreted climate reconstructions; focused excessively on large spatial or temporal scales; identified simplistic dichotomies between vulnerable and resilient societies; devoted insufficient attention to uncertainty; and equated correlation too easily with causation. To overcome these problems, scholars have introduced a research framework consisting of binary questions that encourage greater integration of methods and sources from distinct disciplines (Degroot *et al* 2021).

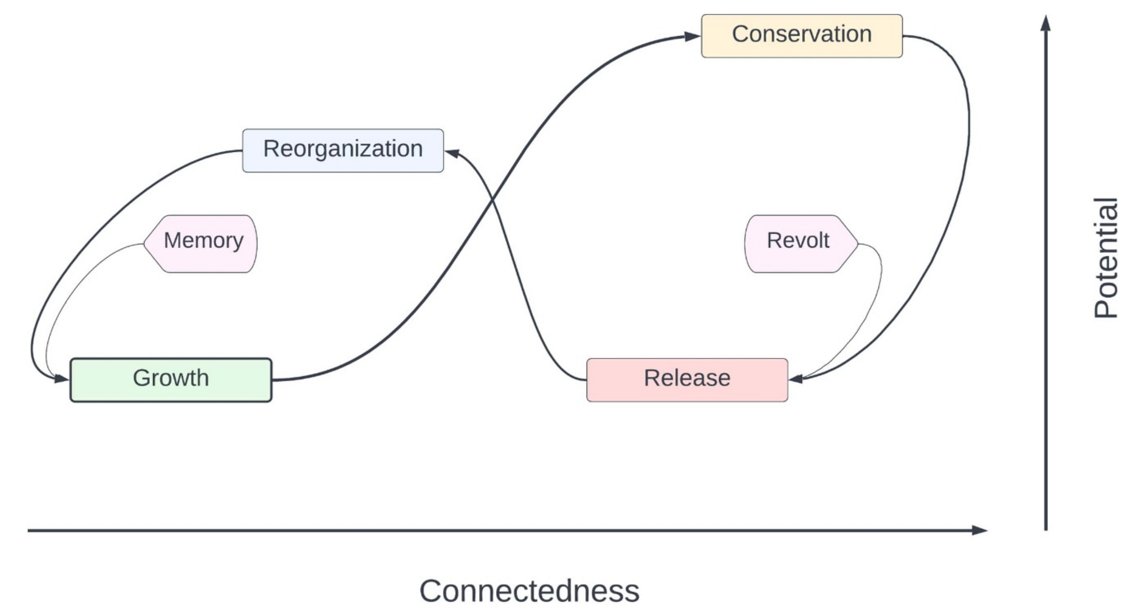
6. Uncovering human responses: models

The models used by geneticists to reconstruct demography depend on the type of data available. Models that reconstruct gradual changes in population sizes through time, such as Bayesian skyline plots of mtDNA or sequentially Markovian coalescent (PSMC) methods for whole genomes, tend to focus on a single population that is assumed to be isolated—meaning it does not receive any migrants—or otherwise on a pair of connected populations (Ho and Shapiro 2011, Mather *et al* 2020). These approaches rely on the logic that lineages are more likely to merge when populations are small, and less likely when populations are large. According to this reasoning, the rate at which lineages merge at different times can be converted to population sizes (although migration will also affect this rate, and thus confound size reconstructions).

Models that consider the relationship among multiple populations (and consequently allow for migration) often require geneticists to define specific events, which can then be tested and quantified. For example, geneticists can identify the presence of population bottlenecks and correlate them with periods of climate change that reduced the productivity and in turn the habitability of local landscapes. Inferred demographic changes, however, have to be interpreted with care. Population genetics models reconstruct effective population sizes (the sizes of an idealized, unstructured and randomly mating population), and these can differ greatly from census population sizes, owing for example to geographic substructuring or marriage practices (e.g. Palstra and Fraser 2012). Climate Informed Spatial Genetic Models have attempted to explicitly reconstruct the possible influence of climate change on demography by matching its predicted impact to the observed patterns of genetic differentiation among contemporary and ancient genomes (e.g. Erikson *et al* 2012, Delser *et al* 2021).

Different aspects of genetic data can be used to define how compatible a model is with empirical evidence. Geneticists can use an explicit likelihood framework, where the best estimates of demographic parameters and their uncertainties can be directly derived, mathematically, from data. Alternatively, they can use simulations, by comparing simulated to observed genetic data using frameworks such as Approximate Bayesian Computation to formally obtain best estimates of demographic parameters and their uncertainties (Sunnaker *et al* 2013). Natural selection can be inferred by looking directly at the frequency of a variant of interest (either by comparing populations under varying degrees of selection, or different time points), as well as the signature that is left behind in sites adjacent to the one of interest (as selection tends to reduce variability around the selected site) (Scheinfeldt and Tishkoff 2013, Vitti *et al* 2013).

Various metrics have been designed to capture and emphasize such signals. A complication in assessing the role of selection is that demographic events (such as bottlenecks) can generate signals that are similar to those arising from selection. However, while demographic signals are spread throughout the whole genome, selection only acts on a few variants. Selection tests take advantage of this latter property by using an outlier approach, where the signature at a locus of interest is compared to the background levels across the whole genome. This approach provides 'candidate' genes that are likely to be under selection (though it has a high rate of false positives; e.g.



Vulnerability	Resilience	Adaptation
The propensity or predisposition to be adversely affected.	The capacity of human and environmental systems to cope with hazards while maintaining their essential function, identity and structure.	The process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit opportunities.

Figure 4. A typical representation of the adaptive cycle (top), and Intergovernmental Panel on Climate Change (IPCC) definitions of vulnerability, resilience, and adaptation (bottom). Many HCS scholars either use the IPCC definitions directly, or develop similar definitions to conceptualize societal responses to past climate change (Haldon and Rosen 2018, Matthews *et al* 2019).

Koropoulis *et al* 2020), and these candidates can then be indirectly linked with climatic drivers (Rees *et al* 2020). A few models have also been developed to directly link the frequency of alleles to climatic drivers by looking for correlations between the frequency of a genetic variant and a climatic variable across contemporary populations (e.g. Hancock *et al* 2008). Recently, techniques have developed to use the time series provided by ancient DNA, which allow a direct observation of the changes resulting from selection (e.g. Schraiber *et al* 2016, Loog *et al* 2017). While these approaches have yet to be used to investigate climatic effects, they hold much promise for the future given the exponential increase in the number of human ancient genomes being recovered.

Correlation in space and time—at different resolutions and with variable methodological rigor—is also often at the heart of archaeological human-environment studies. Yet many archaeologists believe that, unless combined with some form of model for human behavior and culture change, any resulting interpretations remain difficult to substantiate (Contreras 2016), and open to charges of *a priori* deterministic biases inherent in chosen study designs (Arponen *et al* 2019).

Use of terms such as 'resilience,' 'adaptation,' and 'vulnerability' has become widespread in archaeology to characterize human responses to climate change. Many archaeologists have defined resilience as part of Formal Resilience Theory (RT), or simply RT. Central to RT is a method for conceptualizing connections between behavioral adaptations in human populations and external environmental change. This method is based on the Adaptive Cycle (AC) Model, in which social-ecological systems pass through four stages—which may be called growth, conservation, release, and reorganization—that together constitute a single cycle (figure 4). Cycles are nested within each other across different spatiotemporal scales, a feature called 'panarchy,' and connect through 'revolt' and 'remember' feedback loops. These loops represent the nonlinear nature of social responses to climatic changes (meaning their inputs need not be directly proportional to their outputs) (Leroy 2006, Cumming *et al* 2008). The four domains in each cycle have different degrees of 'connectedness' and 'potential,' which in turn gives them different degrees of resilience. Resilience in the model declines as the system gains complexity, and only increases during the reorganization/renewal period (Bradtmöller *et al* 2017).

For HCS scholars, there are advantages to using RT and the AC model. RT arguably provides a powerful tool for overcoming deterministic interpretations of climate change as a direct cause of social change, and it appears to permit straightforward comparisons between case studies of resilience (Hegmon *et al* 2008). Yet archaeologists have long differed over whether the AC model is better suited as a heuristic device or analytical tool, and they have not used the same definitions for components of the model. The model has also been difficult to operationalize when applied to imperfect archaeological datasets (Redman 2005, Bradtmöller *et al* 2017, Brewer and Riede 2018, Heitz *et al* 2021).

Much like geography, the discipline of archaeology is divided between those who see cultural change as largely responsive to internal, political, and ideational forces, and those who would prioritize external forces, such as climatic and environmental change ('internalists' still dominate the discipline of history). Nowhere is this division more obvious than in discussions of past examples of societal 'collapse,' which many archaeologists discern in evidence of widespread site abandonment that seems to suggest demographic decline, elevated rates of conflict, and the disintegration of elite class superstructures. Some scholars argue on the basis of archaeological evidence that past societies collapsed in the face of climatic variability and change (Diamond 2010, Weiss 2017, Zhang *et al* 2021), while others question the evidence for collapse in specific case studies; suggest alternative causal models for collapse; or challenge the concept of collapse itself (Coombes and Barber 2005, Hegmon *et al* 2008, McAnany and Yoffee 2010, Middleton 2017, Haldon *et al* 2020). While these basic attitudes do have subtle consequences for study design and practice, models seeking to combine exogenous and endogenous forces are clearly most promising (Butzer 2012, Butzer and Endfield 2012).

Some archaeologists and historians now stress the potential of archaeological or historical research to conduct 'natural experiments' that compare chosen study units (such as villages, cities, and cultures) before, during, and after a climatic perturbation (Diamond and Robinson 2010, Riede 2014, Manning *et al* 2017, Bauch 2020). In such experiments, societal responses to climate change are always co-determined by the socioeconomic and political conditions in place at the onset of a given perturbation. Both social and climatic changes govern access to resources, which can be identified in archaeological proxies of risk management that in turn approximate vulnerability and resilience (Halstead and O'Shea 1989, Wisner 2004, Riede *et al* 2017). Proxies for adaptation can then be sought in changes visible in archaeological remains that postdate climatic perturbations.

Influenced in part by archaeologists, historians have also adopted the concepts of adaptation, resilience, and vulnerability (Endfield 2014, Izdebski *et al* 2018, Xoplaki *et al* 2018, Degroot 2018c, Degroot *et al* 2021). The widespread use of this terminology in HCS scholarship has helped make theoretical models more applicable across disciplinary boundaries (Engler 2012). Yet while the most influential models in archaeology prioritize change over time, models in history, geography, and economics typically focus on the uneven magnitude of changes across different elements of past societies. In history, for example, the longstanding impact-order model (figure 5) typically conceptualizes climatic changes as having progressively less direct influence on biophysical, economic, social, and cultural transformations within past societies (Pfister 1984, 2007, Kramer 2015, Luterbacher and Pfister 2015, Camenisch and Rohr 2018). Historians originally developed versions of this model to describe societal responses to climatic anomalies in particular times and places, then used it to conceptualize the regional or even continental consequences of climatic trends. They have added complexity to the model by, for example, representing adaptive responses to climate changes, or adding cultural reactions to every impact level (Camenisch *et al* 2016a, Ljungqvist *et al* 2020). Geographers and economists developed similar models to identify how climate change provoked wars and demographic crises, for instane, by reducing agricultural output, although their models more consistently include feedbacks between social changes (Zhang *et al* 2010, 2011, Pei *et al* 2014, Burke *et al* 2015, Cook and Wolkovich 2016).

Recently, some historians have pointed out that the impact order model depends on the assumption that climatic changes had more direct impacts on agriculture or pastoralism than other sectors of society: an assumption that increasingly does not seem to have been accurate in many historical contexts (Degroot 2018b, Degroot *et al* 2021). Indeed, because historians often stress contingency and spatiotemporal particularity in establishing causation, many have been skeptical of normative models—such as the AC model and to some extent the Impact Order model—that generalize across outcomes. Climate historians often benefit from abundant documentary evidence that can reveal human responses to weather in granular detail. As a result, they do not necessarily require models to argue that correlations between climatic and societal changes reveal causation. What some historians call for instead are process models that generalize mechanisms, and thereby provide novel ways to conceptualize how climatic changes spur large-scale social changes. Several recent studies accordingly consider how climate changes influenced the availability, quantity, and character of energy accessible to human populations, but such approaches are still in their infancy (Degroot 2018c).

An older and more influential process model used by historians identifies a 'fatal synergy' between sharp reductions in agricultural output that were triggered or worsened by climatic anomalies, and a host of social ills that further reduced agricultural productivity (figure 6). Repeated harvest failures, according to

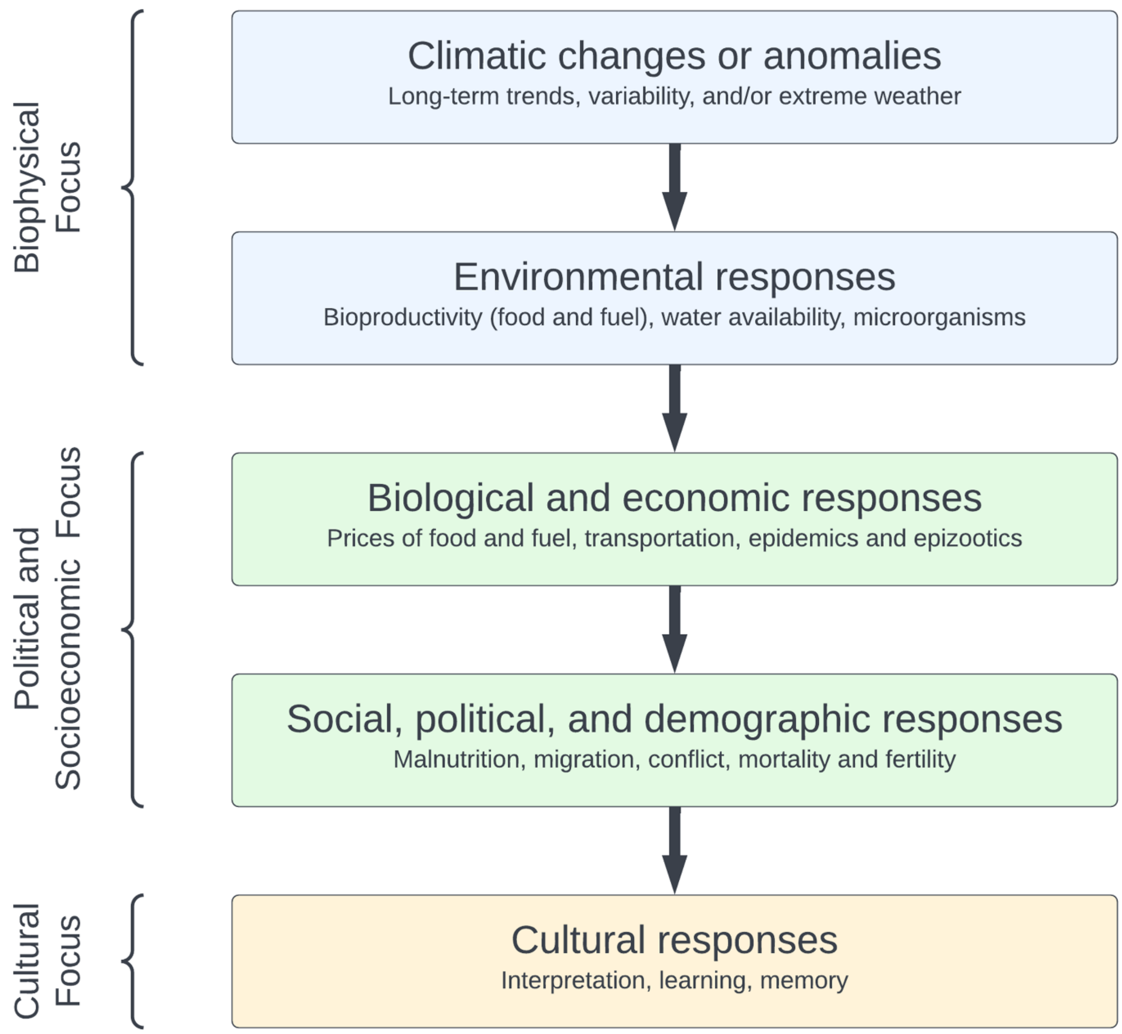


Figure 5. A version of the impact order model widely used by climate historians. In the model, the impacts of climate change become progressively less direct as they filter through environmental; political and socioeconomic; and cultural domains (Camenisch *et al* 2016b).

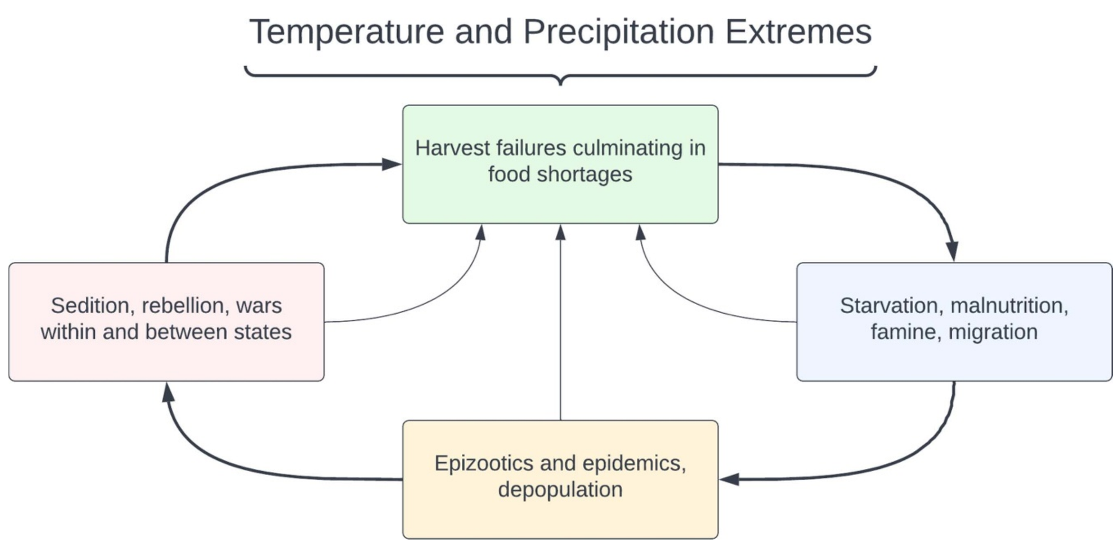


Figure 6. A representation of the 'fatal synergy' that, in influential studies by climate historians, worsened societal crises across large spatial scales that were ultimately triggered by late Holocene climate changes. Feedbacks connect the consequences of harvest failures to the further devastation of agricultural regions (Parker 2013).

the model, ultimately reduced the availability of food and thereby caused widespread malnutrition, starvation, and famine. By altering the range and reproductive rate of disease vectors, and by weakening immune systems in malnourished human and animal bodies, climatic anomalies also spurred the spread of epidemic or epizootic disease. Migration from the famine-stricken countryside circulated epidemics or epizootics, and compounded overcrowding in cities that accordingly grew more vulnerable to epidemic outbreaks. Mortality among human laborers and animals essential to pre-modern agro-economies further reduced food production, and exacerbated widespread depopulation. Amid these disasters popular discontent with ruling authorities—who in some cultures were held directly responsible for weather—spurred sedition, rebellion, and even wars between polities looking to exploit one another's weaknesses. Pre-modern wars further reduced food availability through, for example, the conscription of agricultural laborers, the redirection of grain stocks to armies, and the plundering of the countryside (Parker 2013, Degroot 2018b).

Implicit in the concept of the fatal synergy is once again the assumption that climatic anomalies and changes had a particularly direct impact on agriculture and pastoralism. Yet HCS scholars have used the concept to identify feedbacks that are typically hidden in the Impact Order Model, and help explain how relatively small variations in the climate of the Holocene may have had profoundly destructive, nonlinear consequences for some pre-modern societies (Parker 2013).

7. HCS findings: genetics

Paleogenetic evidence can reveal compelling correlations between demographic changes in human populations and climatic trends. By reconstructing local environmental conditions, HCS scholars can then infer causal links between climatic changes and the migration, expansion, retrenchment, or extirpation of human populations. Such work can suggest—but not confirm—relationships between climatic and human histories in the Pleistocene, which may be difficult to discern using other evidence.

Population genetics played a key role in providing support for a recent 'out-of-Africa' origin of anatomically modern humans (e.g. Cann *et al* 1987, Fu *et al* 2013, Rieux *et al* 2014, Malaspinas *et al* 2016). The timing of the primary out-of-Africa migration inferred from genetics (65–50 000 BP) suggests a link between this range expansion and climatic change. Earlier waves of migration coincided with generally warm and wet conditions that may have 'pulled'—that is, enticed—hunter-gatherers away from their African territories. Yet the primary out-of-Africa migration coincided with exceptionally cold and dry conditions in the Horn of Africa (Liu *et al* 2015, Tierney *et al* 2017a). These conditions may have 'pushed' migrants to leave Africa. Since cold water takes up less volume than warm water, and vast quantities of water were trapped in ice sheets, sea levels were low and a southern migratory route out of Africa was therefore more traversable than it had been (Beyer *et al* 2021, Groucutt *et al* 2021).

Genetic dating of the Pleistocene arrival of modern humans into the Americas (e.g. Raghavan *et al* 2015), together with sedimentary DNA, similarly suggests that the opening of a coastal corridor in the melting Cordilleran ice sheet may have aided migration into the Western Hemisphere after approximately 12 600 BP (Pedersen *et al* 2016). Nevertheless, recent archaeological and genetic evidence suggests far earlier migration into the Americas, when the corridor had not yet appeared (Moreno-Mayar *et al* 2018, Becerra-Valdivia and Higham 2020). Paleogenetic evidence has encouraged HCS scholars to assume causation from approximate correlations, but it can also reveal that population dynamics have long been shaped by much more than climatic conditions.

Population genetics is in fact blind to population movements that resulted in no descendants (or at least, too few to be detectable), and large-scale population expansions often left genetic signatures that are stronger than, and therefore override, those generated by local changes in population (Miller *et al* 2018). Nevertheless, time series of ancient DNA have allowed geneticists to focus on local dynamics, and thereby to uncover that the climatic oscillations of the Pleistocene and early Holocene coincided with profound changes in human communities. Analysis of time series data of aDNA in western Eurasia, for example, shows a clear population bottleneck during the LGM, as well as a major population replacement during the warming period after 14 000 BP (Fu *et al* 2016, Posth *et al* 2016). Populations that persisted in colder climates during the LGM, such as the Western Hunter Gatherers and Caucasus Hunter Gatherers, are characterized by shorter runs of homozygosity (a sign of smaller population sizes) compared to populations from further south, such as the Early Farmers, which may have sustained larger populations owing to comparatively benign climatic conditions (Jones *et al* 2015). Using genetic evidence, regional climatic changes in the Holocene, such as the 4.2 kiloyear aridification of the Arabian Peninsula, have also been correlated with bottlenecks in local populations (Almarri *et al* 2021).

Such correlations between climatic change and human demography cannot easily reveal causation, let alone the motivations for human action. As a result, HCS scholars have attempted more direct tests of the effect of climate on demographics, by linking environmental variables to the level of gene flow (and thus divergence) among contemporary populations. Analyses of modern genomes in Africa (Petkova *et al* 2016) and Eurasia (Pagani *et al* 2016) have suggested that deserts and mountains were long the principal barriers limiting human movement, while coastal areas acted as corridors. Such studies use a static approach in which modern climate is correlated with genetic divergence, but the diachronic effect of climate change is ignored. Recent publications have attempted to explicitly account for the historical influence of climatic changes on demography, by integrating climate reconstructions of the Pleistocene and Holocene within Climate Informed Spatial Genetic Models. In these models, population sizes are either predicted by fluctuating climatic variables such as aridity and temperature, or by primary productivity. The models are able to reconstruct the level of divergence found in both modern (Eriksson *et al* 2012) and ancient genomes (Delser *et al* 2021), and confirm the important role of deserts and mountains in shaping gene flow over time. Moreover, geneticists have found that, in the Holocene, the level of genetic admixture between hunter-gatherers and farmers increased in areas with low Growing Degree Days, a measure of climate that predicts the accumulated heat available for crop growth. Higher mixing—suggesting more interaction between both groups—occurred when and where climatic conditions contributed to less successful food production (Betti *et al* 2020).

Geneticists have also connected shifts in the climates experienced by Pleistocene hunter-gatherers, owing either to migration or orbitally forced climatic changes, to genetic adaptations that persist in human populations. Some of these adaptations are controversial. For example, genetic research has shown that, sometime between 6 and 10 000 BP, a genetic mutation affected the OCA2 gene in European populations and led it to reduce the production of melanin in irises (Eiberg *et al* 2008). The result was the emergence of blue eyes in human populations. The OCA2 mutation may have been an indirect adaptation to climatic warming, because the end of the Younger Dryas in approximately 11 700 BP allowed European populations to live at higher latitudes, where there would have been less sunlight in winter. Blue irises absorb more light than brown irises, and the blue-eyed may have been resistant to Seasonal Affective Disorder caused by lack of winter light. Other geneticists have proposed sexual selection as an important driver for the evolution of blue irises, but this explanation does not necessarily preclude a climatic cause (Workman *et al* 2018). Versions of genes associated with lighter skin—primarily SLC24A5 and SLC45A2—may have emerged at approximately the same time in European populations that had settled across high European latitudes in the wake of the LGM. These genetic versions may have benefited European populations by facilitating vitamin D production when ultraviolet light is limited (Jablonski and Chaplin 2010). However, aDNA has recently revealed that SLC24A5 was associated with the spread of early farmers out of Anatolia, and some Mesolithic hunter-gatherers in Europe had moderately dark skin (e.g. Olalde *et al* 2014, Ju and Mathieson 2021).

Explicit tests for association between SNP frequencies and climatic reconstructions indicate that climate-influenced selection is the likely explanation for the rise in the frequency of some genetic variants (Hancock *et al* 2008, 2011). The variants with the strongest signals tended to be associated with pigmentation and UV radiation, as well as infection and immunity (Hancock *et al* 2008, 2011). Furthermore, such studies have highlighted a number of SNPs (such as LEPR R109K and FABP2 A54T) that are associated with phenotypes favoring cold tolerance (Hancock *et al* 2008). In some instances, variants found to be associated with climate adaptations are known to increase the risk of autoimmune or metabolic diseases, which are likely to be pleiotropic effects of selection for an advantageous phenotype. A number of ailments currently seen in contemporary populations may therefore be the product of past selection to better withstand challenging climatic conditions. For example, geneticists have argued that a mutation in the TRPM8 cold receptor, which is common across higher latitudes, has helped populations regulate body temperatures in cold weather while increasing the prevalence of migraines (Key *et al* 2018). Genetic research has therefore revealed intriguing correlations between climatic changes, local environmental transformations, and genetic mutations, but HCS scholars who use genetic evidence can for the most part only infer causal connections.

8. HCS findings: archaeology

There is now little doubt among archaeologists that, in the broadest sense, early human history was shaped and constrained by climate change. Archaeological evidence supports genetic evidence that correlates changes in hominin populations with climatic shifts during the Pleistocene (Hublin and Roebroeks 2009, Dennell *et al* 2011, Pedersen *et al* 2021, Maier *et al* 2021, Timbrell *et al* 2022, Timmermann *et al* 2022). Archaeologists emphasize, however, that the climatic oscillations of the Pleistocene helped encourage both biological and cultural adaptations within these populations that ultimately enabled environmental modifications by human communities at ever-increasing scales (Roberts and Stewart 2018, Riede 2019, Murray *et al* 2021).

The roots of farming lifestyles stretch back into the Pleistocene, yet the Neolithic Revolution—the widespread dissemination of agriculture and the technological and cultural innovations that accompanied it—unfolded only with the onset of the Holocene (Simmons 2011). Interglacial periods during the Pleistocene were in all probability at least as warm as the Holocene. Yet archaeologists have long argued that the globally warm and stable climate of the Holocene permitted the expansion of agriculture once the selection pressure of earlier cultivation yielded cereals productive enough to sustain human populations (Richerson *et al* 2001). Some archaeologists, however, argue that many hunter-gatherer communities first adopted agriculture only during transitions from warmer and wetter to cooler and drier conditions, which occurred in some occupied regions during the Younger Dryas of the late Pleistocene, and the 8.2 kiloyear event in the early Holocene (Simmons 2011). According to this theory, hunter-gatherer communities that expanded in comparatively benign climatic conditions could not easily accommodate the influence of climate change on the fauna and flora that had sustained them, and many were compelled either to migrate or domesticate plants and animals (Lieberman and Gordon 2018).

The classic case of the transition to agriculture by Late Natufian communities in the Levant provides ample evidence for both theories. For decades, influential archaeologists have argued that regional aridification during the Younger Dryas—which is now disputed by paleoclimatologists—reduced the size of forests and the availability of wild cereals, compelling some Natufian communities to cultivate grains that were increasingly difficult to obtain otherwise (other communities adapted by developing new hunting technologies, but they did not survive) (Bar-yosef 1998, Stein *et al* 2010, Liu *et al* 2013). Excavations of, for example, rye seeds at the Natufian site of Abu Hureyra may suggest that this transition to agriculture coincided with the onset of the Younger Dryas in approximately 13 000 BP. Yet many archaeologists have found evidence that contradicts the idea of a Late Natufian subsistence crisis (Colledge and Conolly 2010). Some conclude that the Late Natufian transition to farming occurred only after the Younger Dryas had subsided. According to this view, growing populations spurred the development of new and more reliable means of obtaining food, and a wet, warm climate made agriculture more viable than it had been (Willcox *et al* 2008, 2009). Archaeological evidence can suggest causation more clearly than genetic evidence alone, yet it is often fragmentary and open to contradictory interpretations. Debates therefore persist over whether communities were pushed or pulled towards agriculture by climate change, and indeed over the extent to which climate change mattered at all (Maher *et al* 2011).

Agriculture where it developed demanded and enabled new forms of storage and stationary infrastructure, which in turn helped some populations withstand climatic trends and anomalies. Agriculture also transformed labor relations and political structures. Most agricultural societies developed to be hierarchical and territorial, a process that while neither universal nor inevitable, eventually culminated in the emergence of states and empires (Graeber and Wengrow 2021). Archaeologists have found that climatic anomalies and trends accelerated some of these developments. Archaeologists and paleoscientists have for example tied the gradual emergence of Pharaonic Egypt to the desertification of northern Africa, which likely inspired some pastoral communities to migrate to the fertile Nile delta (Manning and Timpson 2014, Williams 2021). Indeed some centralized political systems developed because they were able to better coordinate responses to climatic perturbations (Wu *et al* 2016). Yet the commitment to stationary resources in such systems also raised the cost of migration as an adaptive response to climate-induced hardship. Archaeologists have long argued that communities developed distinct and at times contradictory risk management strategies with varying degrees of success, which together contributed to lags between climatic changes and social responses in many societies (Laland and Brown 2006).

Nevertheless, proposed subdivisions in the Holocene can also be understood as periods of large-scale transformation in human societies (Walker *et al* 2019a, 2019b), even if the manifestations of these events varied regionally (LeGrande *et al* 2006, Morrill *et al* 2013). Archaeologists have devoted considerable attention to both the 8.2 and 4.2 kiloyear event. By 8200 BP, lower latitudes were mostly occupied by farming communities, and larger settlement agglomerations, such as Catal Huyük in present-day Turkey, already had populations numbering in the thousands. At higher latitudes, hunter-gatherer-fisher communities had pushed into remote reaches of the Arctic. Archaeologists have shown that the regional manifestations of cooling and drying led to the widespread abandonment of settlements in the eastern Mediterranean, for example, and migration towards the west (Weninger *et al* 2006), likely by depressing agricultural productivity. At the same time, marked cooling in northern Europe and a major North Sea tsunami generated by a massive undersea landslide off the Norwegian coast together led to dramatic population declines (Manninen 2014, Wicks and Mithen 2014, Waddington and Wicks 2017, Manninen *et al* 2018, Jørgensen *et al* 2020).

Archaeologists have found it harder to discern clear correlations between the 8.2 kiloyear event and the trajectories of societies in mid-latitudes (Griffiths and Robinson 2018, Van Maldegem *et al* 2021). Around the Mediterranean and Saharan Africa, aridification associated partly with the 8.2 kiloyear event (see Tierney *et al* 2017b) likely affected population densities (Manning and Timpson 2014), migrations (e.g. Weninger *et al* 2006, Berger and Guilaine 2009) and cultural expressions (e.g. Sereno *et al* 2008), as well as perhaps facilitating the emergence of new forms of social organization (Kuper and Kröpelin 2006). Regional differences in the environmental expressions of this climatic event, coupled with the different background conditions of affected societies, generated widely divergent outcomes for contemporary populations as well as lags and asynchronies between climatic and cultural changes (see Maher *et al* 2011). Some societies were resilient, while others likely underwent some degree of societal collapse.

Ancient Egypt ultimately depended on irrigation agriculture, as did powerful states across Southwest Asia. Other regional states relied on rain-fed farming and extensive pastoralism, while early states across the Indian subcontinent exploited regular monsoon rains. The 4.2 kiloyear event appears to have caused changes in the frequency, timing, and extent of rainfall in these regions (see Jones *et al* 2019). By interpreting evidence from sites such as Tell Leilan in Syria, archaeologists have argued that prolonged drought provoked the collapse of contemporary empires, including most famously the so-called Akkadian Empire (Weiss *et al* 1993, Cullen *et al* 2000, Weiss and Bradley 2001). It now seems that these climatic changes had some influence over the demographic and political development of empires, but also that their impacts varied from region to region and did not devastate every polity (Weiss 2017, Lawrence *et al* 2021, Lawrence *et al* 2021). There were winners and losers in what clearly constituted a complex political landscape (see Scanlon 1988). Archaeologists have found that contemporary polities were both inherently unstable and capable of mounting effective and diverse adaptive responses to climatic perturbations. During the 4.2 kiloyear event, lags caused by these culturally mediated responses may again have weakened chronological correlations between climatic and some social changes, or the climate changes themselves may not have been coeval.

Climatic changes may have hastened the decline of some ancient empires by undermining their agricultural foundations, yet it is often difficult for archaeologists to determine the relative contribution of climatic influences to political and economic trends (Sinha *et al* 2019). These complexities are especially clear in archaeological studies of regional climatic changes and social responses along the Desert and Steppe Silk Roads, which long connected economies and cultures across Eurasia (Yang *et al* 2019). Scholars have linked regional drying trends from 3500 BP to a broad movement towards urbanization and irrigation along the classical Silk Roads, and then a shift towards wetter conditions to the dawn of a golden era in Silk Road trade (Hill 2019). Yet they have also established that regional responses to climatic trends and anomalies were diverse and often effective, depending more on the internal characteristics of communities and societies than the nature or magnitude of environmental change (Panyushkina *et al* 2019, Xu *et al* 2019, Yang *et al* 2019).

Archaeologists have uncovered similarly complex evidence for societal upheavals during the LALIA. In Northern Europe and the Eastern Baltic region, textual sources are absent but archaeological evidence abounds. Archaeological evidence for societal responses to the LALIA remains open to conflicting interpretations (Moreland 2018), but most archaeologists argue that the sixth century was a troubled time in the region, with major breaks in settlement structure, land-use, demography, and cultic practices (Price *et al* 2015, Newfield 2018). Cooling led to years of extreme frost, the spread of cereal fungi, and ultimately poor harvests that culminated in a widespread agricultural crisis (Widgren 2012, Bondeson and Bondesson 2014, Helama *et al* 2018, 2019). Rising mortality may have been exploited strategically by Swedish elites, who acquired abandoned land and thereby increased their political power (Löwenborg 2012). Across Norway and the eastern Baltic, archaeological evidence suggests a sharp decline in cultural activity and population during the LALIA (Tvauri 2014, Solheim and Iversen 2019).

In Denmark, soils were more fertile, growing days were more abundant, and economic connections were closer to the rest of Europe. Archaeological sources suggest that the impacts of the LALIA on Danish communities were accordingly more diverse. They reveal, for example, ritual responses in the form of starkly increased depositioning of valuables related to the contemporaneous Sun-cult. They indicate that while some settlements declined, others were founded, and new decorative designs and power relations emerged (Hoilund Nielsen 2005).

The LALIA may have had even more profound cultural consequences in Scandinavia. Recorded in writing only many centuries later, Nordic eschatology around the 'Fimbulwinter' as omen and prelude to the end of the world—or at least to social order—may have emerged during the LALIA, and could constitute an effort to grapple with the social responses to climatic change that archaeologists have uncovered (Axboe 1999, Gräslund 2007, Gräslund and Price 2012, Nordvig and Riede 2018,van Dijk *et al* preprint). While less information is available from the Americas during the LALIA and therefore the regional climate manifestation and the causes of societal change remains poorly resolved, this period did correspond with a sixth-century Maya 'hiatus' (Curtis *et al* 1996, Dunning *et al* 1999, DeMenocal 2001, Nooren *et al* 2017, Dull *et al* 2019).

Centuries later, during the Medieval Climate Anomaly (MCA), Norse settlers occupied Iceland and parts of coastal Greenland and Canada. Archaeologists once concluded that North Atlantic warming allowed the Norse to establish settlements in Greenland partly by reducing the extent of Arctic sea ice, which made it easier to navigate near Greenland, and by allowing Norse settlers to import agro-pastoral practices from Iceland (Hambrecht 2015). Following this logic, Norse settlements disappeared with the onset of the LIA in the fourteenth and fifteenth centuries because sea ice severed their links with Europe, and subsistence strategies that worked at lower latitudes could no longer function in cooler weather (McGovern 1980, 1981).

Yet many archaeologists—including some responsible for originally characterizing the Norse as inflexible—now emphasize that Norse settlers developed traditional ecological knowledge attuned to diverse environments across the northern Atlantic (Dugmore *et al* 2009, 2013). In Greenland, Norse settlers organized communal labor across dispersed settlements and abandoned cod fishing for communal hunts of migratory harp and hooded seals, which filled a springtime provisioning gap. They learned to build driving lanes for caribou; improve farming through drainage, irrigation, fertilization, and fencing; and acquire live polar bears, narwhal teeth, and walrus tusks and hides for European markets. A vast literature now explores how the flexible Greenlandic Norse adapted to century-scale sea level increases, decadal cooling trends, and interannual weather variability (Dugmore *et al* 2012, Jackson *et al* 2018a).

New explanations for the rise and decline of Norse settlements in Greenland are multicausal (Hambrecht 2015). Summer sea threatened Norse efforts to organize communal labor and travel to walrus hunting grounds that sustained the Norse economy. Rising sea levels eroded lowland pasture, and together with cooling temperatures exacerbated the growing dependency of small farmers on large magnate farms. The relatively small western (northern) settlement disappeared in the fourteenth century CE. The larger eastern (southern) settlement endured by intensifying the communal seal hunt, yet more frequent storms made this an increasingly perilous activity (Dugmore *et al* 2012). The exquisite adaptations that the Norse made to their Greenlandic environment made them more vulnerable when that environment changed (Dugmore *et al* 2013, Jackson *et al* 2018a).

Economic and demographic changes beyond the control of the Greenlandic Norse compounded those vulnerabilities. The migration of potentially hostile and technologically more sophisticated Thule Inuit communities into the outer fjords around the eastern settlement may also have complicated the Norse seal hunt. Moreover, the declining popularity of walrus ivory in Europe—and the growing dominance in Arctic commerce of the Hanseatic League, whose merchants traded fish rather than luxury goods—undermined the foundations of the Greenlandic economy (Barlow *et al* 1997, Dugmore *et al* 2012). The old story of Norse inflexibility is also not entirely without merit. There is no evidence, for example, that the Norse adopted Thule technologies—such as the toggling harpoon—and individualistic hunting practices that would have allowed them to hunt plentiful bearded and ringed seals in winter. Yet the fate of the Norse is now widely interpreted as a case study in the often nonlinear consequences of climate change for populations, which can overwhelm even initially successful adaptation (Dugmore *et al* 2009). The story of human settlement in LIA Greenland is in any case as much a story of Thule resilience as it is Norse collapse, but the Thule experience of climate change has attracted far less attention from archaeologists (Grønnow *et al* 2011).

In recent years, archaeologists have similarly reimagined other charismatic case studies of collapse in the Common Era, outside of the simple framework of the LIA or MCA, that once seemed like straightforward consequences of climatic change or variability. Many of these involve the purported collapse of hydraulic societies, such as the Tiwanaku in the twelfth-century Andes and Angkor in fifteenth-century Cambodia (Binford *et al* 1997, Erickson 1999, Buckley *et al* 2010). Of these examples, the best-known concerns the apparent collapse of Lowland Classic Maya polities across the Yucatan Peninsula in the ninth and tenth centuries CE (Huntington 1913b, Kennett *et al* 2012, Turner and Sabloff 2012, Webster 2012, Marx *et al* 2017). To cope with the lack of surface water in the upland area of the peninsula, the Maya constructed an intricate system of dams, reservoirs, wells, and canals—as well as terraces and check dams to control soil erosion and leaching—that may have left them vulnerable to longer or more frequent fluctuations in precipitation (Douglas *et al* 2016). Paleoclimatologists first discerned evidence for a series of catastrophic ninth- and tenth-century droughts in sediments extracted from Lake Chichancanab, in northern Yucatan. Some paleoclimatologists and some archaeologists argued that these droughts forced the abandonment of Classic Mayan settlements and thereby caused the long-term decline of Mayan culture (Hodell *et al* 1995, Curtis *et al* 1996).

Other scholars, including archaeologists, pointed out that Maya polities in the driest areas were abandoned last, and that the societal, political, and demographic manifestations of collapse had other plausible social causes. Some critics argued that the Classical Maya did not collapse at all; rather, their culture and population merely became less visible in the archaeological record (McAnany and Yoffee 2010). The persistence of Mayan culture and identity subsequently led other scholars and activists to emphasize the resilience of many Maya communities to even the sixteenth-century Spanish Invasion and the late nineteenth-century Caste War (Braswell and Alexander 2014).

Further work in the region has uncovered more and higher resolution paleoclimate evidence—derived most importantly from speleothems—for repeated and severe droughts across the Yucatan Peninsula in and just after the Terminal Classic Period (Kennett *et al* 2012, Douglas *et al* 2016, Medina-Elizalde *et al* 2016). Archaeologists increasingly incorporate these droughts within multicausal explanations for the transformation of Classical Maya society. In these explanations, synergistic pressures including widespread deforestation, owing in part to overpopulation; conflict within and between polities; and the rerouting of trade networks that once passed through the Central Maya Lowlands all rendered many Classical Maya polities increasingly vulnerable to drought (Lucero 2002, Dunning *et al* 2012, Turner and Sabloff 2012). Some Mayan adaptations to climatic variability seem to have mirrored those of the Norse to climatic cooling, and created similar vulnerabilities. Widespread adoption of water-conservative maize cultivation across the lowlands amid droughts in the third through the sixth centuries CE, for example, resembled the adaptive switch to seal hunting by the thirteenth- and fourteenth-century Norse (Ebert *et al* 2017). Owing in part to the inflexibility of Norse and Mayan elites, both strategies seem to have been inadequate and indeed maladaptive in the face of combined climatic, socioeconomic, and political stressors in later decades and centuries (Douglas *et al* 2015, Ebert *et al* 2019).

In any case, there is limited archaeological evidence for mass starvation and mortality in Classical Maya polities, suggesting that these stressors encouraged adaptive migration and resettlement (Turner and Sabloff 2012). Indeed, archaeologists have recently argued that stratified societies in Greater Amazonia that, in pre-Columbian centuries, relied on extensive infrastructure to control water—such as the Classical Maya—were less resilient in the face of prolonged drought than egalitarian societies with diverse and flexible subsistence strategies founded on polyculture agroforestry (De Souza *et al* 2019). Because such societies may be less visible in the archaeological (or historical) record—much like the Thule in Greenland—the emphasis by many HCS archaeologists on collapse may reveal a statist bias. Some archaeologists have argued that what may at first appear in the archaeological record as evidence of catastrophe can also be interpreted as an indication of dramatic but successful adaptation to climatic change or variability.

In sum, the archaeological record offers strong evidence that climatic changes provoked profound transitions in many societies during both the Pleistocene and Holocene. Yet there is also ample archaeological evidence for the persistence of communities and especially cultures amid changing climates. With its wide array of proxies relating to both past economies; trade and power networks; and ideologies and cosmologies, the archaeological record offers insights into the risk management strategies that societies adopted in the face of past climate change. Different forms of societies prioritized different response strategies, with migration the leading strategy for inherently mobile populations of pastoralists and foragers, and the least appealing, costliest option for sedentary agricultural societies. The latter could often draw on more or less effective means of buffering against sustained climate changes, which either delayed the catastrophic impact of such changes or allowed agricultural societies to remain resilient sufficiently long for a given stressor to abate. Most episodes of societal collapse did not lead to the total disappearance of societies, let alone cultures, yet definitions of resilience rooted in cultural persistence should be mindful not to ignore the political, socioeconomic, and especially the demographic costs associated with climate-driven collapses in the archaeological record.

9. HCS findings: history

Historical studies in HCS have long concentrated on periods and places that are well documented by surviving documents and art. This focus partly accounts for the disproportionate attention given by climate historians to Europe, and to some extent its colonies, during the LIA. The widespread adoption in early modern Europe of the printing press coincided with the strengthening of state bureaucracies to encourage the widespread proliferation of documentary evidence for weather and societal responses to weather. Plentiful and diverse documents allow climate historians to identify causal connections between large-scale climate changes, local or regional environmental transformations, and human responses at a much higher resolution than is usually possible for scholars in other disciplines (Pfister and Wanner 2021).

By using archives of societies alongside archives of nature, climate historians have established that temperature and precipitation extremes associated with the coldest decades of the LIA decreased the accessibility and in many cases the availability of food and fuel for communities across Europe. The weather conditions that proved most damaging to contemporary agriculture varied across European regions (White *et al* 2018a). Historians have concluded that in general temperature mattered most for agriculture in Northern Europe, where frost could shorten growing seasons and thereby devastate the autumn harvest. Temperature and precipitation were both equally important for agriculture in Western and Central Europe, where cold in spring and summer, and heavy rains in summer and autumn, typically posed the most severe risks to harvests. In the Mediterranean, springtime droughts were especially damaging, as were bitterly cold winters (Ljungqvist *et al* 2020).

Historians have found that precipitation extremes lowered the quality and quantity of hay for domestic animals, which not only provided food in the way of dairy and meat but also the commodities and labor that sustained agrarian economies (D'Arrigo *et al* 2020). Severe winters killed domestic animals directly and delayed when they could consume fresh grass in the spring, which in turn reduced their milk supply (Baten 2001). Winters are less commonly considered by climate historians than other seasons, partly because they are hard to reconstruct using the archives of nature and, in some cases, those of societies. Yet across Europe frigid winters characteristic of the LIA disrupted plant and animal phenology; ruined stores of food and beer; and interfered with shipments of cereals, dairy products, fish, and freshwater (Cavert 2017, Degroot 2018b). Historical studies suggest that climate anomalies and trends also influenced the distribution and accessibility of wild animals used for food and fuel, such as fish and marine mammals (Hacquebord 1999, Ogilvie and Jónsdóttir 2000, Hoffmann 2005, Degroot 2022).

While historians have long accused HCS scholars of environmental determinism, climate historians increasingly argue that populations were far from helpless when weather associated with the LIA helped cause harvest failures. They have shown for instance that citizens within resilient communities, such as the coastal cities of the seventeenth-century Dutch Republic, benefitted from diverse diets and robust traditions of civic charity (Pfister 1978, Dijkman 2018, Degroot 2018c, Curtis and Dijkman 2019). Governments across Italy, Spain, and France adapted in the immediate aftermath of poor harvests by, for example, distributing cereals from and regulating access to granaries; providing grain subsidies (occasionally by taxing the wealthy) and limiting grain prices; and banning grain exports while arranging for emergency imports (Bauch 2019, Degroot *et al* 2021).

Historians have demonstrated that European governments and communities also pursued long-term strategies that either purposefully or unwittingly helped them adapt to the climatic trends of the LIA. Farmers in Finland deserted newly unproductive farms or adopted new crop varieties and cultivation strategies in the wake of particularly cold decades of the LIA, for example (Huhtamaa and Helama 2017a, 2017b). Across Europe, farmers diversified their crops by adopting rye, oats, or barley, which tolerate cold and wet conditions, or took up animal husbandry and even apiculture (Landsteiner 2001, Mrgic 2011, Tello *et al* 2017). Dutch farmers and guilds developed, refined, or exploited new technologies and transportation networks that allowed them to move agricultural commodities from domestic zones of production to centers of consumption in nearly any weather. Dutch merchants deployed newly efficient ships to dominate much larger trade networks that integrated grain markets and thereby buffered populations from local grain shortages (De Kraker 2017, Degroot 2018c).

Nevertheless, climate historians have long devoted special attention to climatic anomalies during the LIA that overwhelmed communal capacities for resilience and adaptation. Historians contributed to early efforts to link climate change to the disappearance of Norse settlements in western Greenland, for example, then joined archaeologists and paleoscientists to reinterpret what initially seemed like a straightforward case of climate-driven collapse (Utterström 1955, Barlow *et al* 1997, Dugmore *et al* 2012, Jackson *et al* 2018a). Historians have since connected so many other disasters across mainland Europe to the climate of the LIA that several studies now identify periods when temperature and precipitation anomalies, associated in some cases with explosive volcanic eruptions, helped provoke continent-wide subsistence crises (Degroot 2018b).

Historians have, for example, linked European subsistence crises to low temperatures or precipitation extremes in the mid-thirteenth century, the early fourteenth century, the early fifteenth century, and the late sixteenth century (Jordan 1996, Campbell 2016, Camenisch *et al* 2016a, 2016b, Pfister *et al* 2018). Influential studies argue that the seventeenth, eighteenth, and nineteenth centuries were all bookended by periods of extreme weather that helped raise food prices and thereby unleashed fatal synergies across Europe, and occasionally in European colonies (Davis 2002, Pfister 2007, Behringer 2017, Parker 2018). Some historians argue that, in many of these periods, economic, political, and demographic pressures created sources of vulnerability that greatly worsened the synergistic social consequences of frigid, wet, or dry weather. Influential studies identify overpopulation, endemic warfare, and reductions in trade or purchasing power—brought about partly through deflation or inflation—as contributors to vulnerability. Some also emphasize the shortcomings of contemporary governments, which either would not or could not effectively organize to relieve high food prices (Davis 2002, Parker 2013).

Climate historians have therefore consistently argued that, even in recent centuries, fluctuations in temperature and precipitation that were far smaller in magnitude than those already caused by global warming nevertheless plunged large and powerful polities into crisis. Other historians claim however that this conclusion is based more on crude correlation than causation; assigns undue importance to exogenous versus endogenous causes for subsistence crises; or reverses the correct chain of causation by for example conceptualizing climate change as a cause of war, rather than war as a cause of vulnerability to climate change (Warde 2015, Kreike 2021). Some climate historians argue that the proliferation of studies linking the LIA to harvest failures and societal crises reflects how studies are designed and the evidence they use, more than the relationships between past climate change and social outcomes that were most common or consequential (Degroot *et al* 2021).

Nevertheless, in recent decades historians have uncovered many similar connections between LIA climate anomalies and subsistence crises beyond Europe. Historians have argued for example that drought (Cook *et al* 2010a) and perhaps cooling across China and its northern borderlands repeatedly ruined harvests, reduced tax revenues, and inspired revolts against the Ming Dynasty, while encouraging raids by pastoralists that ultimately led to the seventeenth-century ascension of the Qing Dynasty (Brook 2010). They have shown that the rising dependence of the sixteenth-century Ottoman Empire on winter crops grown on semi-arid farmland left it vulnerable to severe drought at the end of the century, which combined with inflation and military requisitions to devastate the countryside. Migrating peasants spread epidemics of bubonic plague and anthrax, and many gathered in rebellious armies that eventually threatened the survival of the empire (White 2011). Historians have claimed that precipitation extremes ruined harvests and thereby undermined empires in sixteenth-century sub-Saharan Africa, inspiring waves of migration just as the European slave trade entrenched itself (Miller 1982, Webb 1995). They have also argued that cooling, drought, and pluvials ruined crops and thereby undermined contemporary colonization efforts in North America, while weakening Indigenous polities that might otherwise have offered stiffer resistance to European settlers (White 2017, Skopyk 2020).

The most compelling metanarrative advanced by climate historians may therefore be that the LIA provoked one or more 'global crises,' when cooling and precipitation extremes caused prolonged food shortages and political upheaval on continental, even hemispheric scales. Yet historians have started to move well beyond their longstanding focus on subsistence crises in agrarian empires. For example, new histories consider not only—or not at all—how climate anomalies helped provoke war, but also how they affected the course of wars already underway (Wickman 2018b, Degroot 2020, 2022). Since most wars have a victor and a loser, such histories reveal that the telltale weather of LIA cold periods in different regions could offer both advantages and disadvantages to contemporary populations (Degroot 2014, Wickman 2015).

Climate historians increasingly consider how populations found ways to thrive during the LIA, often in regions—such as the open sea or across Indigenous North America—that have been largely ignored in previous histories (Endfield 2012, Parker 2013, Wickman 2018a, Degroot 2018c). Some historians join scholars in other disciplines to identify strategies that diverse populations followed to exploit—or at least cope with—climatic anomalies and trends (Adamson *et al* 2018, Degroot *et al* 2021). Historians have also emphasized that some populations and institutions within societies were resilient or adaptive in the face of climate change despite—or because of—the vulnerability of other populations (Soens 2018, Van Bavel *et al* 2018). New histories uncover the agency of people and animals confronted with climate change, and thereby reveal how environments seemingly rendered less productive by the LIA could still be exploited with unprecedented intensity by human communities (White 2014, Degroot 2022). An emerging metanarrative in climate history therefore explicitly contradicts the field's longstanding theme of global crisis by emphasizing diverse, contingent, and occasionally counterintuitive relationships between climatic anomalies and human responses.

While climate historians have long focused on the LIA, which is rich in both historical and paleoclimate data, they increasingly consider earlier periods of climate change. New histories, for example, consider harvest failures and other social consequences of droughts, pluvials, and temperature anomalies during the MCA (Kiss 2019, Kiss and Pribyl 2020, Pribyl 2020). Recently, historians have uncovered and refined case studies of ancient societies that coped with and occasionally succumbed to regional droughts and cold spells (Haldon 2016, Erdkamp *et al* 2021). The LALIA is emerging as a period of special interest for climate historians, though confusion over its likely magnitude, duration, and spatial extent—a partial consequence of the limited textual record of the sixth century CE—has inspired competing 'maximalist' and 'minimalist' interpretations of contemporary social responses (Sessa 2019). Maximalist interpretations draw on fragmentary archaeological, paleoenvironmental, and especially historical evidence to identify large-scale connections between cooling, the spread of plague, mass mortality, and the collapse of societies, especially the Western Roman Empire (McCormick *et al* 2012, Büntgen *et al* 2016, Harper 2017). Minimalist accounts emphasize resilience by concentrating on local relationships between climatic anomalies and social responses that can be clearly identified using surviving sources (Newfield 2016, Haldon *et al* 2018a, Erdkamp 2021).

This division is, in some respects, an exaggerated version of the tension between metanarratives developed by climate historians for the later LIA. It reflects differences between historians over the appropriate integration of historical methods and sources with those of other disciplines, as well as differences over the value of correlation in suggesting causation. It reveals another theme in climate history: the sheer difficulty of establishing widely agreed-upon connections between climate changes and human actions, which have historically unfolded across very different scales in time and space. Similar challenges confront scholars—including increasingly historians—who attempt to use far more abundant evidence than is available for pre-industrial periods to identify links between anthropogenic global warming and, for example, migration and conflict (Selby *et al* 2017).

One of the most important developments in climate history has been a growing 'turn' towards studies that consider the cultural dimensions of climate change (Williamson 2020). Historians and other scholars have long argued that decadal changes in the subjects and even the colors of European paintings reflected the climatic trends of the LIA, or at least the volcanic eruptions that caused its coldest years (Sager 2006, Behringer 2010, Degroot 2018c). They have also claimed that popular understandings of the causes for extreme weather, in central Europe in particular, contributed to the persecution of Jews and accused witches during some of the chilliest decades of the LIA, although other historians have disagreed with these claims (Behringer 1999, Oster 2004, Bell 2008, Leeson and Russ 2018). Recently, some of the most compelling historical work on the cultural dimensions of past climate change examines how and why severe weather was remembered, forgotten, and used to justify political or military projects (Oberholzner 2011, Sundberg 2015, Zilberstein 2016, Skopyk 2020).

Cultural histories of climate change can be problematic, however, when they assume broad connections between modest climatic changes and cultural transformations that had more plausible social, economic, and political causes (Blom 2019). The impact order model has helped historians confront such determinism, at the cost of encouraging the assumption that cultural responses to climate change were inevitably filtered through more direct agricultural and economic responses (Ljungqvist *et al* 2020). Yet recent histories find increasingly diverse and plausible connections between periods of climate change such as the LIA and local cultural expressions, including in architecture, technological development, religious practice, and scientific theory (Degroot 2018c, Barnett 2019, Ray 2019, Pluymers 2020, Fisher 2021, Li *et al* 2021). Climate historians have therefore shown that the human consequences of even modest climate changes can be exceptionally far-reaching, affecting nearly every aspect of lived experience, albeit often in subtle ways that can be difficult to distinguish from other historical influences as they unfolded gradually over time.

10. HCS findings: geography and economics

Most studies in HCS, regardless of their discipline, start when scholars identify one or more correlations between climatic and social change. Many scholars who follow the cause-of-effect method—including nearly all historians—use correlations as a starting point for establishing causation in case studies that are typically constrained in time or space. For them, causation can be identified through inferences based on qualitative as well as quantitative sources, with the caveat that it can never be established with certainty (White and Pei 2020).

Geographers and economists, however, have long pioneered the alternative effect-of-cause method, in which correlations between quantified sources are often not the beginning but the end of research projects (figure 3). If enough statistically significant correlations exist between two datasets, those correlations according to the effect-of-cause method can reveal causation more reliably and precisely than inferences based on qualitative evidence. The challenge for geographers and economists has been to identify evidence for historical changes in human populations that either is quantified or that can be quantified on spatiotemporal scales large enough for them to identify many possible correlations with climatic trends (Degroot 2018a).

This challenge has motivated geographers and some economists to focus on whether wars were historically caused by trends in precipitation and drought. Wars can have precise, quantitative definitions, meaning that a conflict must cross a threshold of combat-related deaths to be labeled a war. Using such definitions, geographers and economists have assumed that for regions with a rich record of textual evidence, the spatial extent, duration, and destructiveness of wars can be identified reliably enough to chart their annual regional frequency over decades, centuries, and in some cases even millennia. They then compare fluctuations in the frequency of war with trends in reconstructed temperature or precipitation. Chinese geographers pioneered these methods by identifying significant correlations between drought, cooling, and conflict across imperial China (Zhang *et al* 2006, 2010). Economists and geographers then found similar correlations in Europe during the LIA, and in sub-Saharan Africa during the period of recent anthropogenic warming (Burke *et al* 2009, Lee *et al* 2019). Together, these studies suggest that cold, dry conditions were perilous for pre-modern states, but also that growth in warm, wet decades could exacerbate destabilizing resource shortages when climatic conditions changed (Fang *et al* 2019).

In recent years, geographers and economists have used statistical methods, such as wavelet analysis and Granger causality tests, to attempt to confirm the causation implied by significant correlations. New work has employed superposed epoch analysis to account for the conclusions of many cause-of-effect studies, which identify lags between climatic and social changes that were caused both by societal adaptations and by the systematic complexities of cascading and compound climate change impacts (Gao *et al* 2021). Some of these methods seem to establish that climate did in fact control the frequency of war and even the likelihood of dynastic collapse in distinct regions, environments, and socioeconomic or political contexts (Gao *et al* 2021, Zhang *et al* 2022). However, scholars have used statistical methods, such as Bayesian modeling, that compensate for some of the shortcomings and uncertainties in war frequency datasets to suggest that correlations detected in earlier studies of, for example, war in Europe did not actually exist (Peregrine 2020, Carleton *et al* 2021a, 2021b).

Nevertheless, many scholars now attempt to find correlations between climatic trends and social changes that are in many cases harder to identify, let alone quantify, than war. Studies focusing on imperial China, for example, have found significant correlations that purportedly reveal causation between climate change and agricultural output, migration, economic performance, technological innovation, and even cultural efflorescence (Jin 2002, Carleton and Hsiang 2016, De Dreu *et al* 2018, Lee and Yue 2020, Pei *et al* 2020). An advantage of such work is that statistical relationships in the past can, in theory, be used to model future connections between climatic and social changes. Yet critics in disciplines other than geography and economics argue for example that scholars have used effect-of-cause methods naively, to quantify what is difficult or impossible to quantify on the basis of surviving evidence (a tendency known as the McNamara Fallacy). Critics also claim that many such studies misuse accessible datasets, compiled in most cases by historians, that were never meant to provide comprehensive statistical information (an observational bias known as the Streetlight Effect) (Adams *et al* 2018, Van Bavel *et al* 2019, Degroot *et al* 2021).

Still, studies by geographers and economists do provide a means by which case studies unearthed by historians or archaeologists can be evaluated systematically across large spatial and temporal scales. Their most important finding so far is that climate anomalies have been inherently destabilizing for societies already suffering from considerable political or socioeconomic stress. While this conclusion seems to echo those of many cause-of-effect studies in history and archaeology, its implications are broader, as it is not limited to specific case studies. At present, publications that purport to show similar relationships between climatic trends and social changes that do not directly involve conflict are not convincing, although they may suggest correlations that can be used as starting points for interdisciplinary scholarship.

11. Consilient research teams and coupled modeling

While scholars in different disciplines have undertaken HCS studies in distinct ways, the field's divisions between disciplines are not always obvious. HCS scholars may, for example, have degrees in several disciplines that are relevant for reconstructing climate changes and identifying their influence on human populations. Close bonds have long connected scholars in two or more of these disciplines. The first HCS studies were developed through the partnership of a geographer with a paleoclimatologist, and paleoclimatologists have long had fruitful collaborations with archaeologists.

Similar connections do not bridge scholars in all the disciplines most involved in HCS studies, however, and many publications in the field consequently misuse climate reconstructions or simplistically assume human responses to climate change. Scholars in disciplines that are often associated with the humanities—such as history—have been largely isolated from paleoscientists, owing partly to the priority given to single-authored books for promotion in these fields; the lack of common standards of evidence, approaches to uncertainty, or understandings of causality between disciplines; and the systematic subordination in collaborative climate scholarship of data that cannot be quantified and modeled (Degroot *et al* 2021). Differences in vocabulary, theory, publication and presentation venues as well as a mismatch between publication incentives create further barriers to collaboration. Recently, climate historians have called for more collaborative, 'consilient' approaches to HCS scholarship that involve the development of research projects by teams with equal numbers of participants in relevant disciplines (Newfield and Labuhn 2017, Haldon *et al* 2018b). Such partnerships can require computational methods for aligning distinct forms of data across radically different scales in time and space. Consilient approaches can slow the career progression of some participating scholars, especially those in academic departments that are not structured to support interdisciplinary research. Yet they can help scholars better account for the complexity of both environmental and social systems, and thereby to identify more convincing causal connections between climatic and societal histories (Degroot *et al* 2021).

Many HCS scholars believe that comparisons between climate and social change in the past cannot provide reliable, transdisciplinary lessons for enhancing present-day sustainability without a robust, mechanistic understanding of underlying socio-environmental systems. Mechanistic models allow scientists to formalize our abstract assumptions and intuitions so they can be tested, communicated, and updated as new information arises. A community-wide approach to computational modeling and model-data integration through consilient research teams has been central to the success of the climate sciences over recent decades (Edwards 2010). However, this approach has yet to diffuse to the human historical sciences, in large part because of the lack of standardized generative models of past societies (Romanowska *et al* 2021).

Complex 'integrated assessment models', rooted in economic theory, are commonly used for such purposes in contemporary sustainability studies but have high data requirements and lack the flexibility and dynamism needed to model diverse societies over their long-term history (Rounsevell *et al* 2014, Donges *et al* 2017, 2020, Schill *et al* 2019). These macroeconomic models operate in relative isolation from their environmental counterparts, for example by using the outputs of previously-run climate models as external inputs rather than running the two in tandem.

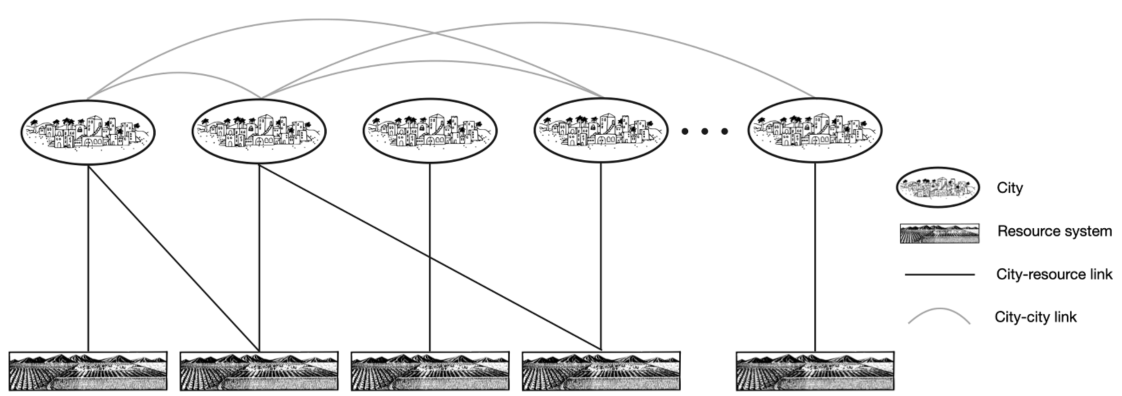


Figure 7. Conceptual diagram of a consumer-resource network, after Qubbaj *et al* (2015), with a network of cities harvesting and exchanging food, water, and energy from their rural surroundings. The behavior of these systems is driven not only by the dynamics of each component in isolation (e.g. population growth in cities, environmental degradation in agricultural regions) but by the various links among these components. Indirect links, such two distant agricultural regions harvested by cities connected by trade, are often as important for system behavior as the direct links visible in the historical and archaeological records.

Alternatively, 'fully coupled' models capture the rich two-way interactions among 'social' and 'natural' subcomponents, exhibiting emergent behaviors such as thresholds, time lags, and feedbacks that are absent from loosely coupled alternatives (Robinson *et al* 2018). A promising coupled modeling approach represents human societies as complex 'consumer-resource networks,' in which interconnected urban systems continuously consume and exchange food, water, energy, and other resources harvested from their rural surroundings (figure 7) (Wilson 2008, Qubbaj *et al* 2015, Dermody *et al* 2018, Dolfing *et al* 2019, O'Dwyer 2020). Although originally rooted in theory from ecology and geography, this basic framework has proven ideal for HCS studies in multiple disciplines including demography (Lee and Tuljapurkar 2008, Puleston and Tuljapurkar 2008, Lee *et al* 2009), ecological economics (Anderies 2006, Motesharrei *et al* 2014, Kuil *et al* 2019), and cultural evolution (Turchin *et al* 2013, Weinberger *et al* 2017).

Consumer-resource models highlight the crucial role of scale and interconnectedness for understanding complex social and environmental systems in the past. These systems are nonlinear; for example, the simulated social response to a drought or flood may have little to do with the magnitude of the event itself, but rather difficult-to-observe details of the society's demography, technology, and social institutions (Anderies 2006, Kuil *et al* 2019). Often, large-scale social responses at one time and place reflect the lingering impacts of seemingly minor shocks in the distant past (Eppinga *et al* 2021) or faraway resource systems (Qubbaj *et al* 2015). Spatial and social networks like roads or exchange systems can either dampen or heighten environmental impacts depending on precise details of the network's structure (Dolfing *et al* 2019). In spite of this potential complexity, these modeling approaches are powerful tools to provide us a 'crude look at the whole' (Gell-Mann 1995)—a relatively simple approximation a system's subcomponents and their mutual interactions—that enable consilient research teams to produce more actionable, real-world insights than would a narrow focus on each discipline in isolation.

12. HCS for the future

Many HCS scholars study the past partly to uncover universally applicable relationships between climatic and social change. In identifying these relationships, many hope to inspire climate activism or contribute to the development of climate policy. Despite this common motivation, scholars in different disciplines have developed distinct methods of using the past to encourage or shape action in the present.

Economists, geographers, and paleoscientists, for example, may draw attention to troubling relationships between climatic and social trends that they have identified in their statistical work. They quantify these relationships and thereby motivate activism that aims, for example, to reduce the likelihood of resource wars in a hotter future. Archaeologists, geneticists, and historians, by contrast, are more likely to develop narratives that chronicle the influence of climate change on a past population, and thereby reveal the extent to which rapid change and warming could shape human affairs. Narratives that explain the collapse or (less commonly) the survival of societies confronted with climate change have attracted considerable public attention (e.g. Diamond 2011) and the concept of collapse is a powerful trope in popular media.

To influence policy, geographers and economists have pioneered econometric methods that use correlations between past climatic and social trends to forecast continued correlations, and therefore causal connections, between these trends in the future (Hsiang *et al* 2013). Scholars in many disciplines have modeled past relationships between climatic and social changes, occasionally in order to identify which social responses to future climate change will be most destructive or most likely to occur (Nelson *et al* 2016, Bauch 2020). Archaeologists and historians have also sought to identify common characteristics in populations that made them either resilient or vulnerable in the face of past climate changes, partly to suggest which qualities governments should emulate or avoid today (Dugmore *et al* 2013, Fang and Zhang 2017, D'Alpoim Guedes and Bocinsky 2018, Reed and Ryan 2019, Riede and Sheets 2020, Degroot *et al* 2021). By drawing on historical examples of civilizational collapse, they have also contributed to studies that suggest scholars and policymakers should more seriously consider the possibility that ecosystems and in turn present-day states will be unable to survive rapid anthropogenic warming (Reichstein *et al* 2021, Kemp *et al* 2022). Some have also identified relationships between past climatic and social changes that scholars in other fields have largely ignored, but may be important in the future (Degroot 2022).

Nevertheless, it can be very difficult for scholars to derive policy-relevant conclusions from HCS scholarship, and then to publish these conclusions in formats that are sensible to policymakers and advisors. This is especially true for scholars in humanistic disciplines—such as history—that typically emphasize contingency and historical particularity. Recently, scholars have drawn attention to the occasionally haphazard and often generalized way that HCS studies draw lessons from inferred long-term changes in ancient societies to inform short-term policy development in today's radically different world (Jackson *et al* 2022, Tubi *et al* 2022). Some HCS scholars even argue that discontinuities between past and present social and climatic contexts are so great that HCS studies can provide few if any lessons for the future (Ray 2019). Yet even the recent past provides many examples of complex communities and societies that coped with profound local and regional climate changes, and ancient populations confronted global changes of far greater scale (D'Alpoim Guedes *et al* 2016). The past inevitably offers an imperfect guide to the future, yet for climate policy—as in other fields—many HCS scholars believe it provides lessons that should not be discounted (Jackson *et al* 2018b, Van Bavel *et al* 2020, Jackson *et al* 2022).

HCS scholarship, however, is generally underrepresented in assessments of the future of climate change and in policy development. When the field is consulted to help policymakers forecast or prepare for the future, statistical studies by geographers and economists are often given preference over qualitative work by scholars in other disciplines (Holm and Winiwarter 2017). Consilient collaborations that involve social scientists and policy advisors are currently being assembled that may help HCS scholars overcome these challenges, and thereby offer unique perspectives on the human future in a warming world (Thomas *et al* 2019).

Data availability statement

No new data were created or analysed in this study.

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References

Adams C, Ide T, Barnett J and Detges A 2018 Sampling bias in climate–conflict research *Nat. Clim. Change* **8** 200–3
Adamson G C D, Hannaford M J and Rohland E J 2018 Re-thinking the present: the role of a historical focus in climate change adaptation research *Glob. Environ. Change* **48** 195–205
PAGES2K Ahmed M, Anchukaitis K, Buckley B M, Braida M, Borgaonkar H P, Asrat A, Cook E R, Büntgen U, Chase B M and Christie D A 2013 Continental-scale temperature variability during the past two millennia *Nat. Geosci.* **6** 339–46
Albrechtsen A, Nielsen F C and Nielsen R 2010 Ascertainment biases in SNP chips affect measures of population divergence *Mol. Biol. Evol.* **27** 2534–47
Alley R B 2000 The Younger Dryas cold interval as viewed from central Greenland *Quat. Sci. Rev.* **19** 213–26
Almarri M A, Haber M, Lootah R A, Hallast P, Al Turki S, Martin H C, Xue Y and Tyler-Smith C 2021 The genomic history of the Middle East *Cell* **184** 4612–25.e14
Anchukaitis K J *et al* 2017 Last millennium Northern Hemisphere summer temperatures from tree rings: part II, spatially resolved reconstructions *Quat. Sci. Rev.* **163** 1–22
Anchukaitis K J, Cook E R, Cook B I, Pearl J, D'Arrigo R and Wilson R 2019 Coupled modes of North Atlantic Ocean-atmosphere variability and the onset of the Little Ice Age *Geophys. Res. Lett.* **46** 12417–26
Anchukaitis K J and Smerdon J E 2022 Progress and uncertainties in global and hemispheric temperature reconstructions of the Common Era *Quat. Sci. Rev.* **286** 107537
Anderies J M 2006 Robustness, institutions, and large-scale change in social-ecological systems: the Hohokam of the Phoenix Basin *J. Institutional Econ.* **2** 133–55
Arponen V P J, Dörfler W, Feeser I, Grimm S, Groß D, Hinz M, Knitter D, Müller-Scheeßel N, Ott K and Ribeiro A 2019 Environmental determinism and archaeology.

Understanding and evaluating determinism in research design *Arch. Dial.* **26** 1–9
Ault T R, Cole J E, Overpeck J T, Pederson G T, St George S, Otto-Bliesner B, Woodhouse C A and Deser C 2013 The continuum of hydroclimate variability in Western North America during the last millennium *J. Clim.* **26** 5863–78
Auton A *et al* (The 1000 Genomes Project Consortium) 2015 A global reference for human genetic variation *Nature* **526** 68–74
Axboe M 1999 The year 536 and the Scandinavian gold hoards *Mediev. Archaeol.* **43** 186–8
Balloux F 2010 The worm in the fruit of the mitochondrial DNA tree *Heredity* **104** 419–20
Bar-Yosef O 1998 The Natufian culture in the Levant, threshold to the origins of agriculture *Evol. Anthropol.* **6** 159–77
Barlow L K, Sadler J P, Ogilvie A E, Buckland P C, Amorosi T, Ingimundarson J H, Skidmore P, Dugmore A J and McGovern T H 1997 Interdisciplinary investigations of the end of the Norse Western Settlement in Greenland *Holocene* **7** 489–99
Barnett L 2019 *After the Flood: Imagining the Global Environment in Early Modern Europe* (Baltimore, MD: Johns Hopkins University Press)
Bartlein P J *et al* 2011 Pollen-based continental climate reconstructions at 6 and 21 ka: a global synthesis *Clim. Dyn.* **37** 775–802
Baten J 2001 Climate, grain production and nutritional status in southern Germany during the 18th century *J. Eur. Econ. Hist.* **30** 9–47
Bauch M 2019 Chronology and impact of a global moment in the 13th century: the Samalas eruption revisited *The Dance of Death in Late Medieval and Renaissance Europe: Environmental Stress, Mortality, and Social Response* ed A Kiss and K Pribyl (London: Routledge) pp 214–32
Bauch M 2020 Impacts of extreme events on medieval societies: insights from climate history *Climate Extremes and Their Implications for Impact and Risk Assessment* ed J Sillmann, S Sippel and S Russo (Amsterdam: Elsevier) pp 279–91
Baumgartner T R, Michaelsen J, Thompson L G, Shen G T, Souta A and Casey R E 1989 The recording of interannual climatic change by high-resolution natural systems: tree-rings, coral bands, glacial ice layers, and marine varves *Aspects of Climate Variability in the Pacific and the Western Americas* vol **55** (Washington, DC: AGU) pp 1–14
Becerra-Valdivia L and Higham T 2020 The timing and effect of the earliest human arrivals in North America *Nature* **584** 93–97
Behringer W 1999 Climatic change and witch hunting: the impact of the Little Ice Age on mentalities *Clim. Change* **43** 335–51
Behringer W 2010 *A Cultural History of Climate* (Cambridge: Polity)
Behringer W 2017 Climate and history: hunger, anti-semitism, and reform during the Tambora crisis of 1815–1820 *German History in Global and Transnational Perspective* ed D Lederer (Berlin: Springer) pp 9–41
Bell D P 2008 The Little Ice Age and the Jews: environmental history and the mercurial nature of Jewish-Christian relations in early modern Germany *AJS Rev.* **32** 1–27
Bell W T and Ogilvie A E J 1978 Weather compilations as a source of data for the reconstruction of European climate during the medieval period *Clim. Change* **1** 331–48
Berger J-F and Guilaine J 2009 The 8200 calBP abrupt environmental change and the Neolithic transition: a Mediterranean perspective *Quat. Int.* **200** 31–49
Berkhofer R 2008 *Fashioning History: Current Practices and Principles* (Berlin: Springer)
Betti L *et al* 2020 Climate shaped how Neolithic farmers and European hunter-gatherers interacted after a major slowdown from 6100 bce to 4500 bce *Nat. Hum. Behav.* **4** 1004–10
Beyer R M, Krapp M, Eriksson A and Manica A 2021 Climatic windows for human migration out of Africa in the past 300 000 years *Nat. Commun.* **12** 4889
Binford L R 1962 Archaeology as anthropology *Am. Antiq.* **28** 217–25
Binford M W, Kolata A L, Brenner M, Janusek J W, Seddon M T, Abbott M and Curtis J H 1997 Climate variation and the rise and fall of an Andean civilization *Quat. Res.* **47** 235–48
Birks H J B, Heiri O, Seppä H and Bjune A E 2010 Strengths and weaknesses of quantitative climate reconstructions based on late-quaternary *Open Ecol. J.* **3** 68–110
Blom P 2019 *Nature's mutiny: How the Little Ice Age of the long seventeenth century transformed the west and shaped the present* Liveright Publishing
Blöschl G *et al* 2020 Current European flood-rich period exceptional compared with past 500 years *Nature* **583** 560–6
Boivin N and Crowther A 2021 Mobilizing the past to shape a better Anthropocene *Nat. Ecol. Evol.* **5** 273–84
Bondeson L and Bondesson T 2014 On the mystery cloud of AD 536, a crisis in dispute and epidemic ergotism: a linking hypothesis *Dan. J. Archaeol.* **3** 61–67
Bova S, Rosenthal Y, Liu Z, Godad S P and Yan M 2021 Seasonal origin of the thermal maxima at the Holocene and the last interglacial *Nature* **589** 548–53
Bradley R S 2014 *Paleoclimatology: Reconstructing Climates of the Quaternary* (Amsterdam: Academic)
Bradtmöller M, Grimm S and Riel-Salvatore J 2017 Resilience theory in archaeological practice—an annotated review *Quat. Int.* **446** 3–16
Braswell G E and Alexander R T 2014 Lessons from the Spanish conquest and the Caste War of the Yucatan *The Ancient Maya of Mexico: Reinterpreting the past of the Northern Maya Lowlands* (London: Routledge) pp 325–48
Brázdil R, Pfister C, Wanner H, Storch H V and Luterbacher J 2005 Historical climatology in Europe: the state of the art *Clim. Change* **70** 363–430
Brewer J and Riede F 2018 Cultural heritage and climate adaptation: a cultural evolutionary perspective for the Anthropocene *World Archaeol.* **50** 554–69
Brierley C M *et al* 2020 Large-scale features and evaluation of the PMIP4-CMIP6 midHolocene simulations *Clim. Past* **16** 1847–72
Brönnimann S *et al* 2019 Last phase of the Little Ice Age forced by volcanic eruptions *Nat. Geosci.* **12** 650–6
Brönnimann S, Pfister C and White S 2018 Archives of nature and archives of societies *The Palgrave Handbook of Climate History* ed S White, C Pfister and F Mauelshagen (New York: Springer) pp 27–36
Brönnimann S and Wintzer J 2019 Climate data empathy *Wiley Interdiscip. Rev.: Clim. Change* **10** 1–8
Brook T 2010 *The Troubled Empire* (Cambridge: Harvard University Press)
Brückner E 1895 Der Einfluß der Klimaschwankungen auf die Ernteerträge und Getreidepreise in Europa *Geogr. Z.* **1** 39–51
Brunt L 2015 Weather shocks and English wheat yields, 1690–1871 *Explor. Econ. Hist.* **57** 50–58
Buckley B M, Anchukaitis K J, Penny D, Fletcher R, Cook E R, Sano M, Nam L C, Wichienkeeo A, Minh T T and Hong T M 2010 Climate as a contributing factor in the demise of Angkor, Cambodia *Proc. Natl Acad. Sci.* **107** 6748–52
Büntgen U *et al* 2016 Cooling and societal change during the Late Antique Little Ice Age from 536 to around 660 AD *Nat. Geosci.* **9** 231–6
Burke M B, Miguel E, Satyanath S, Dykema J A and Lobell D B 2009 Warming increases the risk of Civil War in Africa *Proc. Natl Acad. Sci.* **106** 20670–4
Burke M, Hsiang S M and Miguel E 2015 Global non-linear effect of temperature on economic production *Nature* **527** 235–9
Butzer K W 2012 Collapse, environment, and society *Proc. Natl Acad. Sci.* **109** 3632–9
Butzer K W and Endfield G H 2012 Critical perspectives on historical collapse *Proc. Natl Acad. Sci.* **109** 3628–31
Camenisch C *et al* 2016a The 1430s: a cold period of extraordinary internal climate variability during the early Spörer Minimum with social and economic impacts in north-western and central Europe *Clim. Past* **12** 2107–26

Camenisch C *et al* 2016b The early Spörer minimum–a period of extraordinary climate and socio-economic changes in Western and Central Europe *Clim. Past* **12** 1–33
Camenisch C and Rohr C 2018 The research of climate impacts on society and economy during the Little Ice Age in Europe. An overview *Cuad. Investig. Geogr.* **44** 99
Campbell B M S 2016 *The Great Transition: Climate, Disease and Society in the Late-Medieval World* (Cambridge: Cambridge University Press)
Cann R L, Stoneking M and Wilson A C 1987 Mitochondrial DNA and human evolution *Nature* **325** 31–36
Carleton T A and Hsiang S M 2016 Social and economic impacts of climate *Science* **353** aad9837
Carleton W C, Campbell D and Collard M 2021a A reassessment of the impact of temperature change on European conflict during the second millennium CE using a bespoke Bayesian time-series model *Clim. Change* **165** 1–16
Carleton W C, Collard M, Stewart M and Groucutt H S 2021b A song of neither ice nor fire: temperature extremes had no impact on violent conflict among European societies during the 2nd millennium CE *Front. Earth Sci.* **9** 1074
Carolin S A, Walker R T, Day C C, Ersek V, Sloan R A, Dee M W, Talebian M and Henderson G M 2019 Precise timing of abrupt increase in dust activity in the Middle East coincident with 4.2 ka social change *Proc. Natl Acad. Sci. USA* **116** 67–72
Caseldine C J and Turney C 2010 The bigger picture: towards integrating palaeoclimate and environmental data with a history of societal change *J. Quat. Sci.* **25** 88–93
Caulfield T and Murdoch B 2017 Genes, cells, and biobanks: yes, there's still a consent problem *PLoS Biol.* **15** e2002654
Cavert W 2017 Winter and discontent in early modern England *Governing the Environment in the Early Modern World: Theory and Practice Routledge Environmental Humanities* ed S Miglietti and J Morgan (London: Earthscan)
Chiari S 2019 Climatic issues in early modern England: Shakespeare's views of the sky *WIREs Clim. Change* **10** e578
Churakova O V, Bryukhanova M V, Saurer M, Boettger T, Naurzbaev M M, Myglan V S, Vaganov E A, Hughes M K and Siegwolf R T W 2014 A cluster of stratospheric volcanic eruptions in the AD 530s recorded in Siberian tree rings *Glob. Planet. Change* **122** 140–50
Claw K G, Anderson M Z, Begay R L, Tsosie K S, Fox K and Garrison N A 2018 A framework for enhancing ethical genomic research with Indigenous communities *Nat. Commun.* **9** 2957
Clift P D, Flad R, Fuller D Q and Giosan L 2011 Studying the relationship between past people and their environments *EOS Trans. Am. Geophys. Union* **92** 205
Coats S, Smerdon J E, Cook B I and Seager R 2015 Are simulated megadroughts in the North American Southwest forced? *J. Clim.* **28** 124–42
Coats S, Smerdon J E, Cook B, Seager R, Cook E R and Anchukaitis K J 2016 Internal ocean-atmosphere variability drives megadroughts in Western North America *Geophys. Res. Lett.* **43** 9886–94
Coen D R 2018 *Climate in Motion: Science, Empire, and the Problem of Scale* (Chicago, IL: University of Chicago Press)
Colledge S and Conolly J 2010 Reassessing the evidence for the cultivation of wild crops during the Younger Dryas at Tell Abu Hureyra, Syria *Environ. Archaeol.* **15** 124–38
Contreras D A 2016 Correlation is not enough: building better arguments in the archaeology of human-environment interactions *The Archaeology of Human-Environment Interactions* (London: Routledge) pp 17–36
Cook B I, Cook E R, Anchukaitis K J, Seager R and Miller R L 2011 Forced and unforced variability of twentieth century North American droughts and pluvials *Clim. Dyn.* **37** 1097–110
Cook B I, Mankin J S and Anchukaitis K J 2018 Climate change and drought: from past to future *Curr. Clim. Change Rep.* **4** 164–79
Cook B I, Smerdon J E, Seager R and Cook E R 2014 Pan-continental droughts in North America over the last millennium *J. Clim.* **27** 383–97
Cook B I and Wolkovich E M 2016 Climate change decouples drought from early wine grape harvests in France *Nat. Clim. Change* **6** 715–9
Cook E R, Anchukaitis K J, Buckley B M, D'Arrigo R D, Jacoby G C and Wright W E 2010a Asian monsoon failure and megadrought during the last millennium *Science* **328** 486–9
Cook E R, Seager R, Heim J R R, Vose R S, Herweijer C and Woodhouse C 2010b Megadroughts in North America: placing IPCC projections of hydroclimatic change in a long-term palaeoclimate context *J. Quat. Sci.* **25** 48–61
Coombes P and Barber K 2005 Environmental determinism in Holocene research: causality or coincidence? *Area* **37** 303–11
Crowley T J 2000 Causes of climate change over the past 1000 years *Science* **289** 270–7
Cruikshank J 2001 Glaciers and climate change: perspectives from oral tradition *Arctic* **54** 377–93
Cruikshank J 2007 *Do Glaciers Listen?: Local Knowledge, Colonial Encounters, and Social Imagination* (Vancouver: UBC Press)
Crump S E 2021 Sedimentary ancient DNA as a tool in paleoecology *Nat. Rev. Earth Environ.* **2** 229
Cullen H M, Demenocal P B, Hemming S, Hemming G, Brown F H, Guilderson T and Sirocko F 2000 Climate change and the collapse of the Akkadian empire: evidence from the deep sea *Geology* **28** 379–82
Cumming G S, Barnes G and Southworth J 2008 Environmental asymmetries *Complexity Theory for a Sustainable Future* (New York: Columbia University Press) pp 15–45
Currie A 2018 *Rock, Bone, and Ruin: An Optimist's Guide to the Historical Sciences* (MIT Press)
Curtis D R and Dijkman J 2019 The escape from famine in the Northern Netherlands: a reconsideration using the 1690s harvest failures and a broader Northwest European perspective *Seventeenth Century* **34** 229–58
Curtis J H, Hodell D A and Brenner M 1996 Climate variability on the Yucatan Peninsula (Mexico) during the past 3500 years, and implications for Maya cultural evolution *Quat. Res.* **46** 37–47
D'Alpoim Guedes J A and Bocinsky R K 2018 Climate change stimulated agricultural innovation and exchange across Asia *Sci. Adv.* **4** eaar4491
D'Alpoim Guedes J A, Crabtree S A, Bocinsky R K and Kohler T A 2016 Twenty-first century approaches to ancient problems: climate and society *Proc. Natl Acad. Sci.* **113** 14483–91
D'Arrigo R, Klinger P, Newfield T, Rydval M and Wilson R 2020 Complexity in crisis: the volcanic cold pulse of the 1690s and the consequences of Scotland's failure to cope *J. Volcanol. Geotherm. Res.* **389** 106746
Davis M 2002 *Late Victorian Holocausts: El Niño Famines and the Making of the Third World* (London: Verso)
De Dreu C, van Dijk M A and Lightfoot D A 2018 Climatic shocks associate with innovation in science and technology *PLoS One* **13** e0190122
De Kraker A M 2017 Ice and water. The removal of ice on waterways in the Low Countries, 1330–1800 *Water Hist.* **9** 9109–28
De Luna K M 2016 *Collecting Food, Cultivating People: Subsistence and Society in Central Africa* (New Haven, CT: Yale University Press)
De Souza J G *et al* 2019 Climate change and cultural resilience in late pre-Columbian Amazonia *Nat. Ecol. Evol.* **3** 1007–17
De Vries J 1980 Measuring the impact of climate on history: the search for appropriate methodologies *J. Interdiscip. Hist.* **10** 599–630
Degroot D 2014 "Never such weather known in these seas": climatic fluctuations and the Anglo-Dutch Wars of the seventeenth century, 1652–1674 *Environ. Hist.* **20** 239–73
Degroot D 2018b Climate change and society in the 15th to 18th centuries *WIREs Clim. Change* **9** e518

Degroot D 2018c *The Frigid Golden Age: Climate Change, the Little Ice Age, and the Dutch Republic, 1560–1720* (Cambridge: Cambridge University Press)
Degroot D 2020 Source note: the textual record of climate change at sea *Environ. Hist.* **25** 759–73
Degroot D *et al* 2021 Towards a rigorous understanding of societal responses to climate change *Nature* **591** 539–50
Degroot D 2022 Blood and bone, tears and oil: climate change, whaling, and conflict in the seventeenth-century Arctic *Am. Hist. Rev.* **127** 62–99
Degroot D and Ottens S 2021 Climatological database for the world's oceans online (available at: www.historicalclimatology.com/cliwoc.html)
Degroot D 2018a Climate change and conflict *The Palgrave Handbook of Climate History* ed S White, C Pfister and F Mauelshagen (New York: Springer) pp 367–85
Delser P M *et al* 2021 Climate and mountains shaped human ancestral genetic lineages *bioRxiv Preprint* (https://doi.org/10.1101/2021.07.13.452067) (Accessed 12 September 2022)
DeMenocal P B 2001 Cultural responses to climate change during the late Holocene *Science* **292** 667–73
DeMenocal P B and Tierney J E 2012 Green Sahara: African humid periods paced by Earth's orbital changes *Nat. Educ. Knowl.* **3** 12
Dennell R W, Martinón-Torres M and Bermúdez de Castro J M 2011 Hominin variability, climatic instability and population demography in Middle Pleistocene Europe *Quat. Sci. Rev.* **30** 1511–24
Dermody B J, Sivapalan M, Stehfest E, van Vuuren D P, Wassen M J, Bierkens M F P and Dekker S C 2018 A framework for modelling the complexities of food and water security under globalisation *Earth Syst. Dyn.* **9** 103–18
Diamond J M 2011 *Collapse: How Societies Choose to Fail or Succeed* (New York: Penguin Books)
Diamond J M and Robinson J A 2010 *Natural Experiments of History* (Cambridge, MA: Belknap Press of Harvard University Press)
Diamond J 2010 Two views of collapse *Nature* **463** 880–1
Diaz H F, Trigo R, Hughes M K, Mann M E, Xoplaki E and Barriopedro D 2011 Spatial and temporal characteristics of climate in medieval times revisited *Bull. Am. Meteorol. Soc.* **92** 1487–500
Dijkman J 2018 Bread for the poor: poor relief and the mitigation of the food crises of the 1590s and the 1690s in Berkel, Holland *Famines during the 'Little Ice Age' (1300–1800)* ed D Collet and M Schuh (London: Springer) pp 171–93
Dolfing A G, Leuven J R F W, Dermody B J and Suweis S 2019 The effects of network topology, climate variability and shocks on the evolution and resilience of a food trade network *PLoS One* **14** e0213378
Donges J F *et al* 2020 Earth system modeling with endogenous and dynamic human societies: the copan: CORE open World–Earth modeling framework *Earth Syst. Dyn.* **11** 395–413
Donges J F, Winkelmann R, Lucht W, Cornell S E, Dyke J G, Rockström J, Heitzig J and Schellnhuber H J 2017 Closing the loop: reconnecting human dynamics to Earth System science *Anthr. Rev.* **4** 151–7
Douglas P M J, Demarest A A, Brenner M and Canuto M A 2016 Impacts of climate change on the collapse of lowland Maya civilization *Annu. Rev. Earth Planet. Sci.* **44** 613–45
Douglas P M J, Pagani M, Canuto M A, Brenner M, Hodell D A, Eglinton T I and Curtis J H 2015 Drought, agricultural adaptation, and sociopolitical collapse in the Maya Lowlands *Proc. Natl Acad. Sci.* **112** 5607–12
Douglass A E 1914 A method of estimating rainfall by the growth of trees *Bull. Am. Geogr. Soc.* **46** 321–35
Drake N A, Blench R M, Armitage S J, Bristow C S and White K H 2011 Ancient watercourses and biogeography of the Sahara explain the peopling of the desert *Proc. Natl Acad. Sci.* **108** 458–62
Dugmore A J, Keller C, McGovern T H, Casely A F and Smiarowski K 2009 Norse Greenland settlement and limits to adaptation *Adapting to Climate Change: Thresholds, Values, Governance* ed W N Adger, I Lorenzoni and K L O'Brien (Cambridge: Cambridge University Press) pp 96–113
Dugmore A J, McGovern T H, Streeter R, Madsen C K, Smiarowski K and Keller C 2013 'Clumsy solutions' and 'elegant failures': lessons on climate change adaptation from the settlement of the North Atlantic islands *A Changing Environment for Human Security* ed L Sygna, K O'Brien and J Wolf (London: Routledge) pp 435–51
Dugmore A J, McGovern T H, Vésteinsson O, Arneborg J, Streeter R and Keller C 2012 Cultural adaptation, compounding vulnerabilities and conjunctures in Norse Greenland *Proc. Natl Acad. Sci.* **109** 3658–63
Dull R A *et al* 2019 Radiocarbon and geologic evidence reveal Ilopango volcano as source of the colossal 'mystery' eruption of 539/40 CE *Quat. Sci. Rev.* **222** 105855
Dunning N P, Beach T P and Luzzadder-Beach S 2012 Kax and kol: collapse and resilience in lowland Maya civilization *Proc. Natl Acad. Sci.* **109** 3652–7
Dunning N, Scarborough V, Valdez F, Luzzadder-Beach S, Beach T and Jones J G 1999 Temple mountains, sacred lakes, and fertile fields: ancient Maya landscapes in northwestern Belize *Antiquity* **73** 650–60
Ebert C E, Hoggarth J A, Awe J J, Culleton B J and Kennett D J 2019 The role of diet in resilience and vulnerability to climate change among early agricultural communities in the Maya lowlands *Curr. Anthropol.* **60** 589–601
Ebert C E, May N P, Culleton B J, Awe J J and Kennett D J 2017 Regional response to drought during the formation and decline of Preclassic Maya societies *Quat. Sci. Rev.* **173** 211–35
Edwards P N 2010 *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming* (Cambridge, MA: MIT Press)
Eiberg H, Troelsen J, Nielsen M, Mikkelsen A, Mengel-From J, Kjaer K W and Hansen L 2008 Blue eye color in humans may be caused by a perfectly associated founder mutation in a regulatory element located within the HERC2 gene inhibiting OCA2 expression *Hum. Genet.* **123** 177–87
Emile-Geay J *et al* 2017 A global multiproxy database for temperature reconstructions of the Common Era *Sci. Data* **4** 170088
Endfield G H 2012 The resilience and adaptive capacity of social-environmental systems in colonial Mexico *Proc. Natl Acad. Sci. USA* **109** 3676–81
Endfield G H 2014 Exploring particularity: vulnerability, resilience, and memory in climate change discourses *Environ. Hist.* **19** 303–10
Engler S 2012 Developing a historically based famine vulnerability analysis model (FVAM)—an interdisciplinary approach *Erdkunde* **66** 157–72
Eppinga M B, Siteur K, Baudena M, Reader M O, van't Veen H, Anderies J M and Santos M J 2021 Long-term transients help explain regime shifts in consumer-renewable resource systems *Commun. Earth Environ.* **2** 1–12
Erdkamp P, Manning J G and Verboven K 2021 *Climate Change and Ancient Societies in Europe and the near East: Diversity in Collapse and Resilience* (Cham: Springer International Publishing)
Erdkamp P 2021 Climate change and the productive landscape in the Mediterranean region in the Roman period *Climate Change and Ancient Societies in Europe and the near East* ed P Erdkamp, J G Manning and K Verboven (New York: Springer) pp 411–42
Erickson C L 1999 Neo-environmental determinism and agrarian 'collapse' in Andean prehistory *Antiquity* **73** 634–42
Eriksson A, Betti L, Friend A D, Lycett S J, Singarayer J S, von Cramon-taubadel N, Valdes P J, Balloux F and Manica A 2012 Late Pleistocene climate change and the global expansion of anatomically modern humans *Proc. Natl Acad. Sci.* **109** 16089–94

Esper J *et al* 2012 Orbital forcing of tree-ring data *Nat. Clim. Change* **2** 862–6

Esper J, George S S, Anchukaitis K, D'Arrigo R, Ljungqvist F C, Luterbacher J, Schneider L, Stoffel M, Wilson R and Büntgen U 2018 Large-scale, millennial-length temperature reconstructions from tree-rings *Dendrochronologia* **50** 81–90

Evans J G 2002 *Environmental Archaeology and the Social Order* (New York: Routledge)

Evans M N, Tolwinski-Ward S E, Thompson D M and Anchukaitis K J 2013 Applications of proxy system modeling in high resolution paleoclimatology *Quat. Sci. Rev.* **76** 16–28

Fang X, Su Y, Wei Z and Yin J 2019 Social impacts of climate change in historical China. Socio-environmental dynamics along the historical Silk Road *Socio-Environmental Dynamics along the Historical Silk Road* ed L E Yang, H Bork, X Fang and S Mischke (Cham: Springer) pp 231–45

Fang X and Zhang D 2017 Patterns of the impacts of climate change on civilization *Adv. Earth Sci.* **32** 1218–25

Fernández-Donado L *et al* 2013 Large-scale temperature response to external forcing in simulations and reconstructions of the last millennium *Clim. Past* **9** 393–421

Fisher C 2021 Antebellum black climate science: the medical geography and emancipatory politics of James McCune Smith and Martin Delany *Environ. Hist.* **26** 461–83

Fleming J R 1998 *Historical Perspectives on Climate Change* (Oxford: Oxford University Press)

Frank D C, Esper J, Raible C C, Büntgen U, Trouet V, Stocker B and Joos F 2010 Ensemble reconstruction constraints on the global carbon cycle sensitivity to climate *Nature* **463** 527–30

Fu Q *et al* 2013 A revised timescale for human evolution based on ancient mitochondrial genomes *Curr. Biol.* **23** 553–9

Fu Q *et al* 2016 The genetic history of Ice Age Europe *Nature* **534** 200–5

Gao C, Ludlow F, Matthews J A, Stine A R, Robock A, Pan Y, Breen R, Nolan B and Sigl M 2021 Volcanic climate impacts can act as ultimate and proximate causes of Chinese dynastic collapse *Commun. Earth Environ.* **2** 1–11

García-Herrera R, Können G P, Wheeler D, Prieto M R, Jones P D and Koek F B 2005 CLIWOC: a climatological database for the world's oceans 1750–1854 *Clim. Change* **73** 1–12

García-Herrera R, Barriopedro D, Gallego D, Mellado-Cano J, Wheeler D and Wilkinson C 2018 Understanding weather and climate of the last 300 years from ships' logbooks *WIREs Clim. Change* **9** e544

Gell-Mann M 1995 *The Quark and the Jaguar: Adventures in the Simple and the Complex* (New York: Macmillan)

George S S 2014 An overview of tree-ring width records across the Northern Hemisphere *Quat. Sci. Rev.* **95** 132–50

Glacken C J 1973 *Traces on the Rhodian Shore: Nature and Culture in Western Thought from Ancient Times to the End of the Eighteenth Century* (Berkeley, CA: University of California Press)

Glushkova O Y 2001 Geomorphological correlation of Late Pleistocene glacial complexes of Western and Eastern Beringia *Quat. Sci. Rev.* **20** 405–17

Goosse H, Crespin E, Dubinkina S, Loutre M-F, Mann M E, Renssen H, Sallaz-Damaz Y and Shindell D 2012 The role of forcing and internal dynamics in explaining the "Medieval Climate Anomaly" *Clim. Dyn.* **39** 2847–66

Goosse H, Renssen H, Timmermann A and Bradley R S 2005 Internal and forced climate variability during the last millennium: a model-data comparison using ensemble simulations *Quat. Sci. Rev.* **24** 1345–60

Graeber D and Wengrow D 2021 *The Dawn of Everything: A New History of Humanity* (New York: Farrar, Straus and Giroux)

Gräslund B 2007 Fimbulvintern, Ragnarök och klimatkrisen år 536-537 e. Kr. *Saga och Sed: Kungl. Gustav Adolfs akademiens årsbok* pp 93–123

Gräslund B and Price N 2012 Twilight of the gods? The 'dust veil event' of AD 536 in critical perspective *Antiquity* **86** 428–43

Gray L J *et al* 2010 Solar influences on climate *Rev. Geophys.* **48**

Griffiths S and Robinson E 2018 The 8.2 ka BP Holocene climate change event and human population resilience in northwest Atlantic Europe *Quat. Int.* **465** 251–7

Grønnow B, Gulløv H C, Jakobsen B H, Gotfredsen A B, Kauffmann L H, Kroon A, Pedersen J B T and Sørensen M 2011 At the edge: high Arctic walrus hunters during the Little Ice Age *Antiquity* **85** 960–77

Groucutt H S *et al* 2021 Multiple hominin dispersals into Southwest Asia over the past 400 000 years *Nature* **597** 376–80

Guillet S *et al* 2017 Climate response to the Samalas volcanic eruption in 1257 revealed by proxy records *Nat. Geosci.* **10** 123–8

Gunn J D 2000 *The Years without Summer: Tracing AD 536 and Its Aftermath* (Oxford: Archaeopress)

Hacquebord L 1999 The hunting of the Greenland right whale in Svalbard, its interaction with climate and its impact on the marine ecosystem *Polar Res.* **18** 375–82

Haldon J 2016 *The Empire that Would Not Die: The Paradox of Eastern Roman Survival* vol 13 (Cambridge, MA: Harvard University Press) pp 640–740

Haldon J, Chase A F, Eastwood W, Medina-Elizalde M, Izdebski A, Ludlow F, Middleton G, Mordechai L, Nesbitt J and Turner B 2020 Demystifying collapse: climate, environment, and social agency in pre-modern societies *Millennium* **17** 1–33

Haldon J, Elton H, Huebner S R, Izdebski A, Mordechai L and Newfield T P 2018a Plagues, climate change, and the end of an empire: a response to Kyle Harper's The Fate of Rome (1): climate *Hist. Compass* **16** e12506

Haldon J, Mordechai L, Newfield T P, Chase A F, Izdebski A, Guzowski P, Labuhn I and Roberts N 2018b History meets palaeoscience: consilience and collaboration in studying past societal responses to environmental change *Proc. Natl Acad. Sci.* **115** 3210–8

Haldon J and Rosen A 2018 Society and environment in the East Mediterranean ca 300–1800 CE. Problems of resilience, adaptation and transformation. Introductory essay *Hum. Ecol.* **46** 275–90

Halstead P and O'Shea J 1989 Introduction: cultural responses to risk and uncertainty *Bad Year Economics: Cultural Responses to Risk and Uncertainty* ed P Halstead and J O'Shea (Cambridge: University Press) pp 1–7

Hambrecht G 2015 The first European colonization of the North Atlantic *Historical Archaeologies of Capitalism* ed K Sampeck and L Symanski (Cham: Springer) pp 203–25

Hancock A M *et al* 2011 Adaptations to climate-mediated selective pressures in humans *PLoS Genet.* **7** e1001375

Hancock A M, Witonsky D B, Gordon A S, Eshel G, Pritchard J K, Coop G, Di Rienzo A and Petrov D A 2008 Adaptations to climate in candidate genes for common metabolic disorders *PLoS Genet.* **4** e32

Hannaford M J and Nash D J 2016 Climate, history, society over the last millennium in southeast Africa: climate, history, and society in southeast Africa *WIREs Clim. Change* **7** 370–92

Harper K 2017 *The Fate of Rome: Climate, Disease, and the End of an Empire* (Princeton, NJ: Princeton University Press)

Hegmon M, Peeples M A, Kinzig A P, Kulow S, Meegan C M and Nelson M C 2008 Social transformation and its human costs in the prehispanic U.S. Southwest *Am. Anthropol.* **110** 313–24

Heinrich H 1988 Origin and consequences of cyclic ice rafting in the northeast Atlantic Ocean during the past 130 000 years *Quat. Res.* **29** 142–52

Heitz C, Laabs J, Hinz M and Hafner A 2021 Collapse and resilience in prehistoric archaeology: questioning concepts and causalities in models of climate-induced societal transformations *Climate Change and Ancient Societies in Europe and the near East: Diversity in Collapse and Resilience* ed P Erdkamp, J G Manning and K Verboven (London: Palgrave) pp 127–99

Helama S *et al* 2018 Volcanic dust veils from sixth century tree-ring isotopes linked to reduced irradiance, primary production and human health *Sci. Rep.* **8** 1339

Helama S *et al* 2019 Frost rings in 1627 BC and AD 536 in subfossil pinewood from Finnish Lapland *Quat. Sci. Rev.* **204** 208–15
Helama S, Jones P D and Briffa K R 2017a Dark Ages cold period: a literature review and directions for future research *Holocene* **27** 1600–6
Helama S, Jones P D and Briffa K R 2017b Limited Late Antique cooling *Nat. Geosci.* **10** 242–3
Heymann R and Achermann D 2018 From climatology to climate science in the twentieth century *The Palgrave Handbook of Climate History* ed S White, C Pfister and F Mauelshagen (New York: Springer) pp 605–32
Hill D J 2019 Climate change and the rise of the Central Asian Silk Roads *Socio-Environmental Dynamics along the Historical Silk Road* ed L E Yang, H Bork, X Fang and S Mischke (Cham: Springer) pp 247–59
Ho S Y W and Shapiro B 2011 Skyline-plot methods for estimating demographic history from nucleotide sequences *Mol. Ecol. Resour.* **11** 423–34
Hodell D A, Curtis J H and Brenner M 1995 Possible role of climate in the collapse of Classic Maya civilization *Nature* **375** 391–4
Hoffmann R C 2005 A brief history of aquatic resource use in medieval Europe *Helgol. Mar. Res.* **59** 22–30
Hoilund Nielsen K 2005 "… the sun was darkened by day and the moon by night..there was distress among men"—on social and political development in 5th-to 7th-century southern Scandinavia *Stud. Sachsenforsch.* **15** 247–85
Holm P and Winiwarter V 2017 Climate change studies and the human sciences *Glob. Planet. Change* **156** 115–22
Howell M C and Prevenier W 2001 *From Reliable Sources: An Introduction to Historical Methods* (Ithaca, NY: Cornell University Press)
Hsiang S M, Burke M and Miguel E 2013 Quantifying the influence of climate on human conflict *Science* **341** 1212
Hu J, Emile-Geay J and Partin J 2017 Correlation-based interpretations of paleoclimate data–where statistics meet past climates *Earth Planet. Sci. Lett.* **459** 362–71
Hublin J-J and Roebroeks W 2009 Ebb and flow or regional extinctions? On the character of Neandertal occupation of northern environments *C. R. Palevol* **8** 503–9
Hughes M and Ammann C 2009 The future of the past—an earth system framework for high resolution paleoclimatology: editorial essay *Clim. Change* **94** 247–59
Huhtamaa H and Helama S 2017a Distant impact: tropical volcanic eruptions and climate-driven agricultural crises in seventeenth-century Ostrobothnia, Finland *J. Hist. Geogr.* **57** 40–51
Huhtamaa H and Helama S 2017b Reconstructing crop yield variability in Finland: long-term perspective of the cultivation history on the agricultural periphery since ad 760 *Holocene* **27** 3–11
Hunt B 2011 Global characteristics of pluvial and dry multi-year episodes, with emphasis on megadroughts *Int. J. Climatol.* **31** 1425–39
Huntington E 1913a Changes of climate and history *Am. Hist. Rev.* **18** 213–32
Huntington E 1913b The shifting of climatic zones as illustrated in Mexico. Part I *Bull. Am. Geogr. Soc.* **45** 1–12
Huntington E 1917a *Civilization and Climate* (New Haven, CT: Yale University Press)
Huntington E 1917b Climatic change and agricultural exhaustion as elements in the fall of Rome *Q. J. Econ.* **31** 173–208
Hussain S T and Riede F 2020 Paleoenvironmental humanities: challenges and prospects of writing deep environmental histories *WIREs Clim Change* **11** e667
Inkpen R and Wilson G P 2009 Explaining the past: abductive and Bayesian reasoning *Holocene* **19** 329–34
Izdebski A *et al* 2016 Realising consilience: how better communication between archaeologists, historians and natural scientists can transform the study of past climate change in the Mediterranean *Quat. Sci. Rev.* **136** 5–22
Izdebski A, Mordechai L and White S 2018 The social burden of resilience: a historical perspective *Hum. Ecol.* **46** 291–303
Jablonski N G and Chaplin G 2010 Human skin pigmentation as an adaptation to UV radiation *Proc. Natl Acad. Sci. USA* **107** 8962–8
Jackson R C, Dugmore A J, Harrison R, Hartman S, Madsen C and McGovern T H 2022 Success and failure in the Norse North Atlantic: origins, pathway divergence, extinction and survival *Perspectives on Public Policy in Societal-Environmental Crises* ed A Izdebski, J Haldon and P Filipkowskipp (Cham: Springer) pp 247–72
Jackson R C, Dugmore A J and Riede F 2018b Rediscovering lessons of adaptation from the past *Glob. Environ. Change* **52** 58–65
Jackson R, Arneborg J, Dugmore A, Madsen C, McGovern T, Smiarowski K and Streeter R 2018a Disequilibrium, adaptation, and the Norse settlement of Greenland *Hum. Ecol.* **46** 665–84
Jevons W S 1875 Influence of the sun-spot period on the price of corn *Nature* **15** 1–25
Jin G 2002 Mid-Holocene climate change in North China, and the effect on cultural development *Chin. Sci. Bull.* **47** 408–13
Johnsen S J, Dahl-Jensen D, Gundestrup N, Steffensen J P, Clausen H B, Miller H, Masson-Delmotte V, Sveinbjörnsdottir A E and White J 2001 Oxygen isotope and palaeotemperature records from six Greenland ice-core stations: camp century, Dye-3, GRIP, GISP2, Renland and NorthGRIP *J. Quat. Sci.* **16** 299–307
Johnsen S, Clausen H, Dansgaard W, Fuhrer K, Gundestrup N, Hammer C, Iversen P, Jouzel J, Stauffer B and Steffensen J P 1992 Irregular glacial interstadials recorded in a new Greenland ice core *Nature* **359** 311–3
Jones E R *et al* 2015 Upper Palaeolithic genomes reveal deep roots of modern Eurasians *Nat. Commun.* **6** 8912
Jones M D *et al* 2019 20 000 years of societal vulnerability and adaptation to climate change in southwest Asia *WIREs Water* **6** e1330
Jones P D *et al* 2009 High-resolution palaeoclimatology of the last millennium: a review of current status and future prospects *Holocene* **19** 3–49
Jordan W C 1996 *The Great Famine* (Princeton, NJ: Princeton University Press)
Jørgensen E K, Pesonen P and Tallavaara M 2020 Climatic changes cause synchronous population dynamics and adaptive strategies among coastal hunter-gatherers in Holocene northern Europe *Quat. Res.* **108** 1–16
Ju D and Mathieson I 2021 The evolution of skin pigmentation-associated variation in West Eurasia *Proc. Natl Acad. Sci. USA* **118** e2009227118
Juggins S and Birks H J B 2012 Quantitative environmental reconstructions from biological data *Tracking Environmental Change Using Lake Sediments* ed H J B Birks, A F Lotter, S Juggins and J P Smol (Berlin: Springer) pp 431–94
Jungclaus J H *et al* 2010 Climate and carbon-cycle variability over the last millennium *Clim. Past* **6** 723–37
Kaufman D *et al* 2020b A global database of Holocene paleotemperature records *Sci. Data* **7** 1–34
Kaufman D, McKay N, Routson C, Erb M, Dätwyler C, Sommer P S, Heiri O and Davis B 2020a Holocene global mean surface temperature, a multi-method reconstruction approach *Sci. Data* **7** 1–13
Kemp L *et al* 2022 Climate endgame: exploring catastrophic climate change scenarios *Proc. Natl Acad. Sci.* **119** e2108146119
Kennett D J *et al* 2012 Development and disintegration of Maya political systems in response to climate change *Science* **338** 788–91
Key F M, Abdul-Aziz M A, Mundry R, Peter B M, Sekar A, D'Amato M, Dennis M Y, Schmidt J M, Andrés A M and Gojobori T 2018 Human local adaptation of the TRPM8 cold receptor along a latitudinal cline *PLoS Genet.* **14** e1007298

Kiss A 2019 *Floods and Long-Term Water-Level Changes in Medieval Hungary* (Cham: Springer)
Kiss A and Pribyl K 2020 The dance of death in Late Medieval and Renaissance Europe *Environmental Stress, Mortality and Social Response* (London: Routledge)
Kopp R E, Simons F J, Mitrovica J X, Maloof A C and Oppenheimer M 2009 Probabilistic assessment of sea level during the last interglacial stage *Nature* **462** 863–7
Koropoulis A, Alachiotis N and Pavlidis P 2020 Detecting positive selection in populations using genetic data *Statistical Population Genomics Methods in Molecular Biology* vol 2090, ed J Y Dutheil (New York: Springer) pp 87–123
Kramer D 2015 *"Menschen grasten nun mit dem vieh": Die letzte grosse hungerkrise der schweiz 1816/17* (Basel: Schwabe Basel)
Kreike E 2021 *Scorched Earth: Environmental Warfare as a Crime against Humanity and Nature* (Cambridge: Cambridge University Press)
Kuil L, Carr G, Prskawetz A, Salinas J L, Viglione A and Blöschl G 2019 Learning from the ancient Maya: exploring the impact of drought on population dynamics *Ecol. Econ.* **157** 1–16
Kuper R and Kröpelin S 2006 Climate-controlled Holocene occupation in the Sahara: motor of Africa's evolution *Science* **313** 803–7
Laland K N and Brown G R 2006 Niche construction, human behavior, and the adaptive-lag hypothesis *Evol. Anthropol.* **15** 95–104
Landsteiner E 2001 Trübselige Zeit? Auf der Suche nach den wirtschaftlichen und sozialen Dimensionen des Klimawandels im späten 16.Jahrhundert.Österreichische *Zeitschrift für Geschichtswissenschaften* **12** 77–106
Lang D J, Wiek A, Bergmann M, Stauffacher M, Martens P, Moll P, Swilling M and Thomas C J 2012 Transdisciplinary research in sustainability science: practice, principles, and challenges *Sustain. Sci.* **7** 25–43
Larsen L B *et al* 2008 New ice core evidence for a volcanic cause of the AD 536 dust veil *Geophys. Res. Lett.* **35** L04708
Lawrence D, Palmisano A, de Gruchy M W and Biehl P F 2021 Collapse and continuity: a multi-proxy reconstruction of settlement organization and population trajectories in the Northern Fertile Crescent during the 4.2kya rapid climate change event *PLoS One* **16** e0244871
Lawrence D, Philip G and Gruchy M W 2022 Climate change and early urbanism in Southwest Asia: a review *WIREs Clim. Change* **13** e741
Lee C T, Puleston C O and Tuljapurkar S 2009 Population and prehistory III: food-dependent demography in variable environments *Theor. Popul. Biol.* **76** 179–88
Lee C T and Tuljapurkar S 2008 Population and prehistory I: food-dependent population growth in constant environments *Theor. Popul. Biol.* **73** 473–82
Lee H F and Yue R P H 2020 Ocean/atmosphere interaction and Malthusian catastrophes on the northern fringe of the Asian summer monsoon region in China, 1368–1911 *J. Quat. Sci.* **35** 974–86
Lee H F, Zhang D D, Brecke P and Pei Q 2019 Climate change, population pressure, and wars in European history *Asian Geogr.* **36** 29–45
Leeson P T and Russ J W 2018 Witch trials *Econ. J.* **128** 2066–105
LeGrande A, Schmidt G, Shindell D, Field C, Miller R, Koch D, Faluvegi G and Hoffmann G 2006 Consistent simulations of multiple proxy responses to an abrupt climate change event *Proc. Natl Acad. Sci.* **103** 837–42
Lehner F, Born A, Raible C C and Stocker T F 2013 Amplified inception of European Little Ice Age by sea ice–ocean–atmosphere feedbacks *J. Clim.* **26** 7586–602
Leroy S A G 2006 From natural hazard to environmental catastrophe: past and present *Quat. Int.* **158** 4–12
Li S, Ding K, Ding A, He L, Huang X, Ge Q and Fu C 2021 Change of extreme snow events shaped the roof of traditional Chinese architecture in the past millennium *Sci. Adv.* **7** eabh2601
Lieberman B D and Gordon E 2018 *Climate Change in Human History: Prehistory to the Present* (London: Bloomsbury Academic)
Liu T, Broecker W S and Stein M 2013 Rock varnish evidence for a Younger Dryas wet period in the Dead Sea basin *Geophys. Res. Lett.* **40** 2229–35
Liu W *et al* 2015 The earliest unequivocally modern humans in southern China *Nature* **526** 696–9
Livingstone D N 1991 The moral discourse of climate: historical considerations on race, place and virtue *J. Hist. Geogr.* **17** 413–34
Ljungqvist F C, Seim A and Huhtamaa H 2020 Climate and society in European history *Wiley Interdiscip. Rev.* **12** e691
Lockwood M 2012 Solar influence on global and regional climates *Surv. Geophys.* **33** 503–34
Löfverström M and Liakka J 2016 On the limited ice intrusion in Alaska at the LGM *Geophys. Res. Lett.* **43** 11–030
Loog L *et al* 2017 Inferring allele frequency trajectories from ancient DNA indicates that selection on a chicken gene coincided with changes in Medieval husbandry practices *Mol. Biol. Evol.* **34** 1981–90
Löwenborg D 2012 An Iron Age shock doctrine: did the AD 536–7 event trigger large-scale social changes in the Mälaren valley area? *J. Archaeol. Anc. Hist.* **4** 3–29
Lucero L J 2002 The collapse of the Classic Maya: a case for the role of water control *Am. Anthropol.* **104** 814–26
Lücke L J, Schurer A P, Wilson R and Hegerl G C 2021 Orbital forcing strongly influences seasonal temperature trends during the last millennium *Geophys. Res. Lett.* **48** e2020GL088776
Luterbacher J and Pfister C 2015 The year without a summer *Nat. Geosci.* **8** 246–8
Maher L A, Banning E B and Chazan M 2011 Oasis or mirage? Assessing the role of abrupt climate change in the prehistory of the southern Levant *Camb. Archaeol. J.* **21** 1–30
Maier A, Stojakowits P, Mayr C, Pfeifer S, Preusser F, Zolitschka B and Veres D 2021 Cultural evolution and environmental change in Central Europe between 40 and 15 ka *Quaternary International* **581** 225–40
Malaspinas A-S *et al* 2016 A genomic history of Aboriginal Australia *Nature* **538** 207–14
Manninen M A 2014 Culture, Behaviour, and the 8200 cal BP Cold Event: Organisational Change and Culture Environment Dynamics in Late Mesolithic Northern Fennoscandia *PhD Dissertation* University of Helsinki
Manninen M A, Tallavaara M and Seppä H 2018 Human responses to early Holocene climate variability in eastern Fennoscandia *Quat. Int.* **465** 287–97
Manning J G, Ludlow F, Stine A R, Boos W R, Sigl M and Marlon J R 2017 Volcanic suppression of Nile summer flooding triggers revolt and constrains interstate conflict in ancient Egypt *Nat. Commun.* **8** 900
Manning K and Timpson A 2014 The demographic response to Holocene climate change in the Sahara *Quat. Sci. Rev.* **101** 28–35
Marcott S A, Shakun J D, Clark P U and Mix A C 2013 A reconstruction of regional and global temperature for the past 11 300 years *science* **339** 1198–201
Marsicek J, Shuman B N, Bartlein P J, Shafer S L and Brewer S 2018 Reconciling divergent trends and millennial variations in Holocene temperatures *Nature* **554** 92–96
Marx W, Haunschild R and Bornmann L 2017 The role of climate in the collapse of the Maya civilization: a bibliometric analysis of the scientific discourse *Climate* **5** 88
Masson-Delmotte V, Schulz M, Abe-Ouchi A, Beer J, Ganopolski A, Rouco J G, Jansen E, Lambeck K, Luterbacher J and Naish T 2013 Information from paleoclimate archives *Climate Change 2013—The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed T Stocker, D Quin, G Plattner, M Tignor, S Allen, J Boschung, A Nauels, Y Xia, V Bex and P Midgley (Cambridge: Cambridge University Press) pp 383–464

Mather N, Traves S M and Ho S Y W 2020 A practical introduction to sequentially Markovian coalescent methods for estimating demographic history from genomic data *Ecol. Evol.* **10** 579–89

Matthews J B R (Intergovernmental Panel on Climate Change) 2019 Annex I: glossary *IPCC, 2018: Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* ed V Masson-Delmotte *et al*

Mauelshagen F 2018 Climate as a scientific paradigm—early history of climatology to 1800 *The Palgrave Handbook of Climate History* ed S White, C Pfister and F Mauelshagen (New York: Springer) pp 565–88

Mayewski P A, Rohling E E, Stager J C, Karlén W, Maasch K A, Meeker L D and Steig E J 2004 Holocene climate variability *Quat. Res.* **62** 243–55

McAnany P A and Yoffee N 2010 Questioning how different societies respond to crises *Nature* **464** 977

McCormick M *et al* 2012 Climate change during and after the Roman empire: reconstructing the past from scientific and historical evidence *J. Interdiscip. Hist.* **43** 169–220

McCormick M 2019 Climates of history, histories of climate: from history to archaeoscience *J. Interdiscip. Hist.* **50** 3–30

McGovern T H 1980 Cows, harp seals, and churchbells: adaptation and extinction in Norse Greenland *Hum. Ecol.* **8** 245–75

McGovern T H 1981 The economics of extinction in Norse Greenland *Climate and History: Studies in past Climates and Their Impact on Man* ed T Wigley, M J Ingram and G Farmer (Cambridge: Cambridge University Press) pp 404–33

McGregor H V *et al* 2015 Robust global ocean cooling trend for the pre-industrial Common Era *Nat. Geosci.* **8** 671–7

Medina-Elizalde M, Burns S J, Polanco-Martínez J M, Beach T, Lases-Hernández F, Shen C-C and Wang H-C 2016 High-resolution speleothem record of precipitation from the Yucatan Peninsula spanning the Maya Preclassic period *Glob. Planet. Change* **138** 93–102

Middleton G D 2017 *Understanding Collapse: Ancient History and Modern Myths* (Cambridge: Cambridge University Press)

Miller E F, Manica A and Amos W 2018 Global demographic history of human populations inferred from whole mitochondrial genomes *R. Soc. Open Sci.* **5** 180543

Miller J C 1982 The significance of drought, disease and famine in the agriculturally marginal zones of West-Central Africa1 *J. Afr. Hist.* **23** 17–61

Moreland J 2018 AD536—back to nature? *Acta Archaeol.* **89** 91–111

Moreno-Mayar J V, Vinner L, de Barros Damgaard P, De La Fuente C, Chan J, Spence J P and Willerslev E 2018 Early human dispersals within the Americas *Science* **362** eaav2621

Morgan R 2018 Climate and empire in the nineteenth century *The Palgrave Handbook of Climate History* ed S White, C Pfister and F Mauelshagen (New York: Springer) pp 589–603

Morrill C, Anderson D M, Bauer B A, Buckner R, Gille E P, Gross W S, Hartman M and Shah A 2013 Proxy benchmarks for intercomparison of 8.2 ka simulations *Clim. Past* **9** 423–32

Motesharrei S, Rivas J and Kalnay E 2014 Human and nature dynamics (HANDY): modeling inequality and use of resources in the collapse or sustainability of societies *Ecol. Econ.* **101** 90–102

Mrgic J 2011 Wine or raki-the interplay of climate and society in early modern Ottoman Bosnia *Environ. Hist.* **17** 613–37

Murphy C and Fuller D Q 2017 The future is long-term: past and current directions in environmental archaeology *Gen. Anthropol.* **24** 1–10

Murray J K, Benitez R A and O'Brien M J 2021 The extended evolutionary synthesis and human origins: archaeological perspectives *Evol. Anthropol.* **30** 4–7

Nash D J, Adamson G C, Ashcroft L, Bauch M, Camenisch C, Degroot D, Gergis J, Jusopović A, Labbé T and Lin K-H E 2021 Climate indices in historical climate reconstructions: a global state-of-the-art *Clim. Past Discuss.* **17** 1–48

Nelson M C *et al* 2016 Climate challenges, vulnerabilities, and food security *Proc. Natl Acad. Sci. USA* **113** 298–303

PAGES2k Consortium Neukom R, Barboza L A, Erb M P, Shi F, Emile-Geay J, Evans M N, Franke J, Kaufman D S, Lücke L and Rehfeld K 2019 Consistent multi-decadal variability in global temperature reconstructions and simulations over the Common Era *Nat. Geosci.* **12** 643

Neukom R, Steiger N, Gómez-Navarro J J, Wang J and Werner J P 2019 No evidence for globally coherent warm and cold periods over the preindustrial Common Era *Nature* **571** 550–4

Newfield T P 2016 Mysterious and mortiferous clouds: the climate cooling and disease burden of late antiquity *Late Antiq. Archaeol.* **12** 89–115

Newfield T P and Labuhn I 2017 Realizing consilience in studies of pre-instrumental climate and pre-laboratory disease *J. Interdiscip. Hist.* **48** 211–40

Newfield T P 2018 The climate downturn of 536–50 *The Palgrave Handbook of Climate History* ed S White, C Pfister and F Mauelshagen (New York: Springer) pp 447–93

Nielsen R 2004 Population genetic analysis of ascertained SNP data *Hum. Genomics* **1** 218

Nooren K *et al* 2017 Explosive eruption of El Chichón volcano (Mexico) disrupted 6th century Maya civilization and contributed to global cooling *Geology* **45** 175–8

Nordvig M and Riede F 2018 Are there echoes of the AD 536 event in the Viking Ragnarok myth? A critical appraisal *Environ. Hist.* **24** 303–24

O'Dwyer J P 2020 Stability constrains how populations spread risk in a model of food exchange *One Earth* **2** 269–83

Oberholzner F 2011 From an act of god to an insurable risk: the change in the perception of hailstorms and thunderstorms since the Early Modern Period *Environ. Hist.* **17** 133–52

Ogilvie A E J and Jónsdóttir I 2000 sea ice, climate, and icelandic fisheries in the eighteenth and nineteenth centuries *Arctic* **53** 383–94

Olalde I *et al* 2014 Derived immune and ancestral pigmentation alleles in a 7000-year-old Mesolithic European *Nature* **507** 225–8

Orlando L *et al* 2021 Ancient DNA analysis *Nat. Rev. Methods Primers* **1** 14

Osman M B, Tierney J E, Zhu J, Tardif R, Hakim G J, King J and Poulsen C J 2021 Globally resolved surface temperatures since the Last Glacial Maximum *Nature* **599** 239–44

Oster E 2004 Witchcraft, weather and economic growth in Renaissance Europe *J. Econ. Perspect.* **18** 215–28

Oster J L, Ibarra D E, Winnick M J and Maher K 2015 Steering of westerly storms over western North America at the Last Glacial Maximum *Nat. Geosci.* **8** 201–5

Otto-Bliesner B L *et al* 2021 Large-scale features of Last Interglacial climate: results from evaluating the lig127k simulations for the Coupled Model Intercomparison Project (CMIP6)–Paleoclimate Modeling Intercomparison Project (PMIP4) *Clim. Past* **17** 63–94

Pagani L *et al* 2016 Genomic analyses inform on migration events during the peopling of Eurasia *Nature* **538** 238–42

PAGES Hydro2k Consortium 2017 Comparing proxy and model estimates of hydroclimate variability and change over the Common Era *Clim. Past* **13** 1851–900

Palmisano A, Lawrence D, de Gruchy M W, Bevan A and Shennan S 2021 Holocene regional population dynamics and climatic trends in the Near East: A first comparison using archaeo-demographic proxies *Quat. Sci. Rev.* **252** 106739

Palstra F P and Fraser D J 2012 Effective/census population size ratio estimation: a compendium and appraisal *Ecol. Evol.* **2** 2357–65

Panyushkina I P, Macklin M G, Toonen W H and Meko D M 2019 Water supply and ancient society in the Lake Balkhash

Basin: runoff variability along the historical Silk Road *Socio-Environmental Dynamics along the Historical Silk Road* ed L E Yang, H Bork, X Fang and S Mischke (Cham: Springer) pp 379–410
Parker G 2013 *Global Crisis: War, Climate Change and Catastrophe in the Seventeenth Century* (New Haven, CT: Yale University Press)
Parker G 2018 History and climate: the crisis of the 1590s reconsidered *Climate Change and Cultural Transition in Europe C* Leggewie and F Mauelshagen (Leiden: Brill) pp 119–55
Pedersen J B, Maier A and Riede F 2021 A punctuated model for the colonisation of the Late Glacial margins of northern Europe by Hamburgian hunter-gatherers *Quartär—Int. Jahrbuch zur Erforschung des Eiszeitalters und der Steinzeit* **65** 85–104
Pedersen M W *et al* 2016 Postglacial viability and colonization in North America's ice-free corridor *Nature* **537** 45–49
Pei Q, Zhang D D, Fei J and Hui P Y 2020 Demographic crises of different climate phases in preindustrial Northern Hemisphere *Hum. Ecol.* **48** 519–27
Pei Q, Zhang D D, Lee H F, Li G and Petraglia M D 2014 Climate change and macro-economic cycles in pre-industrial Europe *PLoS One* **9** e88155
Peltier W R, Argus D and Drummond R 2015 Space geodesy constrains ice age terminal deglaciation: the global ICE-6G_C (VM5a) model *J. Geophys. Res.* **120** 450–87
Peregrine P N 2020 Climate and social change at the start of the Late Antique Little Ice Age *Holocene* **30** 1643–8
Petkova D, Novembre J and Stephens M 2016 Visualizing spatial population structure with estimated effective migration surfaces *Nat. Genet.* **48** 94–100
Pettersson O 1914 Climatic variations in historic and prehistoric time *Climatic Variations in Historic and Prehistoric Time* (Berlin: Springer)
Pfister C 1978 Climate and economy in eighteenth-century Switzerland *J. Interdiscip. Hist.* **9** 223
Pfister C 1984 *Klimageschichte der Schweiz (1525–1860) und seine Bedeutung in der Geschichte von Vevölkerung und Landwirtschaft* (Bern: Paul Haupt)
Pfister C 2007 Climatic extremes, recurrent crises and witch hunts: strategies of European societies in coping with exogenous shocks in the late sixteenth and early seventeenth centuries *Mediev. Hist. J.* **10** 33–73
Pfister C, Brázdil R, Luterbacher J, Ogilvie A E and White S 2018 Early Modern Europe *The Palgrave handbook of climate history* 265–95
Pfister C 2018 Evidence from the archives of societies: documentary evidence—overview *The Palgrave Handbook of Climate History* ed S White, C Pfister and F Mauelshagen (New York: Springer) pp 37–47
Pfister C and Wanner H 2021 *Climate and Society in Europe the Last Thousand Years* (Bern: Haupt Verlag)
Pluymers K 2020 Cow trials, climate change, and the causes of violence *Environmental History* **25** 287–309
Pollard A M 1999 Geoarchaeology: an introduction *Geol. Soc. Spec. Publ.* **165** 7–14
Posth C *et al* 2016 Pleistocene mitochondrial genomes suggest a single major dispersal of non-Africans and a late glacial population turnover in Europe *Curr. Biol.* **26** 827–33
Pribyl K 2020 A survey of the impact of summer droughts in southern and eastern England, 1200–1700 *Clim. Past* **16** 161027–41
Price N, Gräslund B and Riede F 2015 Excavating the Fimbulwinter? Archaeology, geomythology and the climate event (s) of AD 536 *Past Vulnerability. Volcanic Eruptions and Human Vulnerability in Traditional Societies past and Present* (Aarhus: Aarhus University Press) pp 109–32 Riede F
Puleston C O and Tuljapurkar S 2008 Population and prehistory II: space-limited human populations in constant environments *Theor. Popul. Biol.* **74** 147–60
Qubbaj M R, Shutters S T and Muneepeerakul R 2015 Living in a network of scaling cities and finite resources *Bull. Math. Biol.* **77** 390–407
Raghavan M *et al* 2015 Genomic evidence for the Pleistocene and recent population history of Native Americans *Science* **349** aab3884
Ray S 2019 *Climate Change and the Art of Devotion: Geoaesthetics in the Land of Krishna 1550–1850* (Seattle, WA: University of Washington Press)
Redman C L 2005 Resilience theory in archaeology *Am. Anthropol.* **107** 70–77
Reed K and Ryan P 2019 Lessons from the past and the future of food *World Archaeol.* **51** 1–16
Rees J S, Castellano S and Andrés A M 2020 The genomics of human local adaptation *Trends Genet.* **36** 415–28
Reichstein M, Riede F and Frank D 2021 More floods, fires and cyclones—plan for domino effects on sustainability goals *Nature* **592** 347–9
Richerson P J, Boyd R and Bettinger R L 2001 Was agriculture impossible during the Pleistocene but mandatory during the Holocene? A climate change hypothesis *Am. Antiq.* **66** 387–411
Riede F 2014 Towards a science of past disasters *Nat. hazards* **71** 335–62
Riede F 2019 Niche construction theory and human biocultural evolution *Handbook of Evolutionary Research in Archaeology* ed A M Prentiss (Cham: Springer International Publishing) pp 337–58
Riede F, Oetelaar G A and VanderHoek R 2017 From crisis to collapse in hunter-gatherer societies. A comparative investigation of the cultural impacts of three large volcanic eruptions on past hunter-gatherers *Crisis to Collapse. The Archaeology of Social Breakdown* ed T Cunningham and J Driessen (Louvain: UCL Presses Universitaires de Louvain) pp 23–39
Riede F and Sheets P 2020 *Going Forward by Looking Back: Archaeological Perspectives on Socio-ecological Crisis, Response, and Collapse* (New York: Berghahn Books)
Rieux A, Eriksson A, Li M, Sobkowiak B, Weinert L A, Warmuth V and Balloux F 2014 Improved calibration of the human mitochondrial clock using ancient genomes *Mol. Biol. Evol.* **31** 2780–92
Roberts P and Stewart B A 2018 Defining the 'generalist specialist' niche for Pleistocene Homo sapiens *Nat. Hum. Behav.* **2** 542–50
Robinson D T *et al* 2018 Modelling feedbacks between human and natural processes in the land system *Earth Syst. Dyn.* **9** 895–914
Robock A 1979 The "Little Ice Age": Northern Hemisphere average observations and model calculations *Science* **206** 1402–4
Rohling E J and Pälike H 2005 Centennial-scale climate cooling with a sudden cold event around 8200 years ago *Nature* **434** 975–9
Romanowska I, Wren C D and Crabtree S A 2021 *Agent-based Modeling for Archaeologists. Simulating the Complexity of Societies* (Santa Fe, NM: SFI Press)
Rounsevell M D A *et al* 2014 Towards decision-based global land use models for improved understanding of the Earth system *Earth Syst. Dyn.* **5** 117–37
Ruddiman W F 2006 Orbital changes and climate *Quat. Sci. Rev.* **25** 3092–112
Sager I 2006 *The Little Ice Age and 17th Century Dutch Landscape Painting, a Study on the Impact of Climate on Art* (Carson, CA: California State University, Dominguez Hills)
Sandweiss D H and Kelley A R 2012 Archaeological contributions to climate change research: the archaeological record as a paleoclimatic and paleoenvironmental archive *Annu. Rev. Anthropol.* **41** 371–91
Scanlon T J 1988 Winners and losers: some thoughts about the political economy of disaster *Int. J. Mass Emerg. Disasters* **6** 47–63

Scheinfeldt L B and Tishkoff S A 2013 Recent human adaptation: genomic approaches, interpretation and insights *Nat. Rev. Genet.* **14** 692–702

Schill C, Anderies J M, Lindahl T, Folke C, Polasky S, Cárdenas J C, Crépin A-S, Janssen M A, Norberg J and Schlüter M 2019 A more dynamic understanding of human behaviour for the Anthropocene *Nat. Sustain.* **2** 1075–82

Schleussner C F and Feulner G 2013 A volcanically triggered regime shift in the subpolar North Atlantic Ocean as a possible origin of the Little Ice Age *Clim. Past* **9** 1321–30

Schneider L, Smerdon J E, Büntgen U, Wilson R J S, Myglan V S, Kirdyanov A V and Esper J 2015 Revising midlatitude summer temperatures back to A.D. 600 based on a wood density network *Geophys. Res. Lett.* **42** 4556–62

Schraiber J G, Evans S N and Slatkin M 2016 Bayesian inference of natural selection from Allele frequency time series *Genetics* **203** 493–511

Schurer A P, Tett S F B and Hegerl G C 2014 Small influence of solar variability on climate over the past millennium *Nat. Geosci.* **7** 104–8

Selby J, Dahi O S, Fröhlich C and Hulme M 2017 Climate change and the Syrian civil war revisited *Polit. Geogr.* **60** 232–44

Sereno P C *et al* 2008 Lakeside cemeteries in the Sahara: 5000 years of holocene population and environmental change *PLoS One* **3** 1–22

Sessa K 2019 The new environmental fall of Rome: a methodological consideration *J. Late Antiq.* **12** 211–55

Siart C, Forbriger M and Bubenzer O 2017 *Digital Geoarchaeology: New Techniques for Interdisciplinary Human-Environmental Research* (New York: Springer)

Sigl M *et al* 2015 Timing and climate forcing of volcanic eruptions for the past 2500 years *Nature* **523** 543–9

Sigsgaard E E, Jensen M R, Winkelmann I E, Møller P R, Hansen M M and Thomsen P F 2020 Population-level inferences from environmental DNA—current status and future perspectives *Evol. Appl.* **13** 245–62

Simmons A H 2011 *The Neolithic Revolution in the near East: Transforming the Human Landscape* (Tucson, AZ: University of Arizona Press)

Sinha A *et al* 2019 Role of climate in the rise and fall of the Neo-Assyrian Empire *Sci. Adv.* **5** eaax6656

Skopyk B 2020 *Colonial Cataclysms: Climate, Landscape, and Memory in Mexico's Little Ice Age* (Tucson, AZ: University of Arizona Press)

Slawinska J and Robock A 2018 Impact of volcanic eruptions on decadal to centennial fluctuations of Arctic sea ice extent during the last millennium and on initiation of the Little Ice Age *J. Clim.* **31** 2145–67

Smerdon J E and Pollack H N 2016 Reconstructing Earth's surface temperature over the past 2000 years: the science behind the headlines *Wiley Interdiscip. Rev. Clim. Change* **7** 746–71

Snyder C W 2016 Evolution of global temperature over the past two million years *Nature* **538** 226–8

Soens T 2018 Resilient societies, vulnerable people: coping with North Sea Floods Before 1800* *Past Present* **241** 143–77

Solheim S and Iversen F 2019 The mid-6th century crises and their impacts on human activity and settlements in southeastern Norway *Settlement Change Across Medieval Europe: Old Paradigms and New Vistas* (Leiden: Sidestone Press) Brady N and Theune C pp 423–34

Stein M, Torfstein A, Gavrieli I and Yechieli Y 2010 Abrupt aridities and salt deposition in the post-glacial Dead Sea and their North Atlantic connection *Quat. Sci. Rev.* **29** 567–75

Stevenson S, Timmermann A, Chikamoto Y, Langford S and DiNezio P 2015 Stochastically generated north american megadroughts *J. Clim.* **28** 1865–80

Stoffel M *et al* 2015 Estimates of volcanic-induced cooling in the Northern Hemisphere over the past 1500 years *Nat. Geosci.* **8** 784–8

Storozum M J, Zhang J, Wang H, Ren X, Qin Z and Li L 2019 Geoarchaeology in China: historical trends and future prospects *J. Archaeol. Res.* **27** 91–129

Sundberg A 2015 Claiming the past: history, memory, and innovation following the christmas flood of 1717 *Environ. Hist.* **20** 238–61

Sunnåker M, Busetto A G, Numminen E, Corander J, Foll M, Dessimoz C and Wodak S 2013 Approximate Bayesian computation *PLoS Comput. Biol.* **9** e1002803

Tassoul J and Tassoul M 2004 *A Concise History of Solar and Stellar Physics* (Berlin: De Gruyter)

Tello E, Martínez J L, Jover-Avellà G, Olarieta J R, García-Ruiz R, de Molina M G, Badia-Miró M, Winiwarter V and Koepke N 2017 The onset of the english agricultural revolution: climate factors and soil nutrients *J. Interdiscip. Hist.* **47** 445–74

Thomas E R, Wolff E W, Mulvaney R, Steffensen J P, Johnsen S J, Arrowsmith C, White J W C, Vaughn B and Popp T 2007 The 8.2 ka event from Greenland ice cores *Quat. Sci. Rev.* **26** 70–81

Thomas K, Hardy R D, Lazrus H, Mendez M, Orlove B, Rivera-collazo I, Roberts J T, Rockman M, Warner B P and Winthrop R 2019 Explaining differential vulnerability to climate change: a social science review *Wiley Interdiscip. Rev.: Clim. Change* **10** e565

Tierney J E *et al* 2020a Past climates inform our future *Science* **370** eaay3701

Tierney J E, deMenocal P B and Zander P D 2017a A climatic context for the out-of-Africa migration *Geology* **45** 1023–6

Tierney J E, Pausata F S R and deMenocal P B 2017b Rainfall regimes of the Green Sahara *Sci. Adv.* **3** e1601503

Tierney J E, Smerdon J E, Anchukaitis K J and Seager R 2013 Multidecadal variability in East African hydroclimate controlled by the Indian Ocean *Nature* **493** 389–92

Tierney J E, Zhu J, King J, Malevich S B, Hakim G J and Poulsen C J 2020b Glacial cooling and climate sensitivity revisited *Nature* **584** 569–73

Tierney J E, Zhu J, King J, Malevich S B, Hakim G J and Poulsen C J 2020 Glacial cooling and climate sensitivity revisited *Nature* **584** 569–73

Timbrell L, Grove M, Manica A, Rucina S and Blinkhorn J 2022 A spatiotemporally explicit paleoenvironmental framework for the Middle Stone Age of eastern Africa *Sci. Rep.* **12** 3689

Timmermann A *et al* 2022 Climate effects on archaic human habitats and species successions *Nature* **604** 495–501

Timmreck C 2012 Modeling the climatic effects of large explosive volcanic eruptions *Wiley Interdiscip. Rev.: Clim. Change* **3** 545–64

Tingley M P, Craigmile P F, Haran M, Li B, Mannshardt E and Rajaratnam B 2012 Piecing together the past: statistical insights into paleoclimatic reconstructions *Quat. Sci. Rev.* **35** 1–22

Toohey M, Krüger K, Sigl M, Stordal F and Svensen H 2016 Climatic and societal impacts of a volcanic double event at the dawn of the Middle Ages *Clim. Change* **136** 401–12

Torfstein A, Goldstein S L, Kushnir Y, Enzel Y, Haug G and Stein M 2015 Dead Sea drawdown and monsoonal impacts in the Levant during the last interglacial *Earth Planet. Sci. Lett.* **412** 235–44

Tubi A, Mordechai L, Feitelson E, Kay P and Tamir D 2022 Can we learn from the past? Towards better analogies and historical inference in society-environmental change research *Glob. Environ. Change* **76** 102570

Turchin P, Currie T E, Turner E A L and Gavrilets S 2013 War, space, and the evolution of Old World complex societies *Proc. Natl Acad. Sci.* **110** 16384–9

Turner B L and Sabloff J A 2012 Classic Period collapse of the Central Maya Lowlands: insights about human-environment relationships for sustainability *Proc. Natl Acad. Sci.* **109** 13908–14

Tvauri A 2014 The impact of the climate catastrophe of 536–537 AD in Estonia and neighbouring areas *Eesti Arheoloogia Ajakiri* **18** 30–56

Ummenhofer C C, D'Arrigo R D, Anchukaitis K J, Buckley B M and Cook E R 2013 Links between Indo-Pacific climate variability and drought in the Monsoon Asia Drought Atlas *Clim. Dyn.* **40** 1319–34

Utterström G 1955 Climatic fluctuations and population problems in early modern history *Scand. Econ. Hist. Rev.* **3** 3–47

Van Bavel B J P, Curtis D R, Hannaford M J, Moatsos M, Roosen J and Soens T 2019 Climate and society in long-term perspective: opportunities and pitfalls in the use of historical datasets *WIREs Clim. Change* **10** e611

Van Bavel B, Curtis D R and Soens T 2018 Economic inequality and institutional adaptation in response to flood hazards *Ecol. Soc.* **23** 30

Van Bavel B, Curtis D, Dijkman J, Hannaford M, De Keyzer M, Van Onacker E and Soens T 2020 *Disasters and History: The Vulnerability and Resilience of past Societies* (Cambridge: Cambridge University Press)

van der Valk T *et al* 2021 Million-year-old DNA sheds light on the genomic history of mammoths *Nature* **591** 265–9

Van Dijk E, Mørkestøl Gundersen I, de Bode A, Høeg H, Loftsgarden K, Iversen F, Timmreck C, Jungclaus J and Krüger K Climate and society impacts in Scandinavia following the 536/540 CE volcanic double event *Clim. Past* preprint (https://doi.org/10.5194/cp-2022-23)

Van Maldegem E, Vandendriessche H, Verhegge J, Sergant J, Meylemans E, Perdaen Y, Lauryssen F, Smolders E and Crombé P 2021 Population collapse or human resilience in response to the 9.3 and 8.2 ka cooling events: a multi-proxy analysis of Mesolithic occupation in the Scheldt basin (Belgium) *J. Anthropol. Archaeol.* **64** 101348

Vitti J J, Grossman S R and Sabeti P C 2013 Detecting natural selection in genomic data *Annu. Rev. Genet.* **47** 97–120

Waddington C and Wicks K 2017 Resilience or wipe out? Evaluating the convergent impacts of the 8.2 ka event and Storegga tsunami on the Mesolithic of northeast Britain *J. Archaeol. Sci. Rep.* **14** 692–714

Waelbroeck C, Labeyrie L, Michel E, Duplessy J C, Mcmanus J F, Lambeck K, Balbon E and Labracherie M 2002 Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records *Quat. Sci. Rev.* **21** 295–305

Walker M *et al* 2019a Formal subdivision of the Holocene series/epoch: a summary *J. Geol. Soc. India* **93** 135–41

Walker M *et al* 2019b Subdividing the Holocene series/epoch: formalization of stages/ages and subseries/subepochs, and designation of GSSPs and auxiliary stratotypes *J. Quat. Sci.* **34** 173–86

Wang Y J, Cheng H, Edwards R L, An Z, Wu J, Shen C-C and Dorale J A 2001 A high-resolution absolute-dated late Pleistocene monsoon record from Hulu Cave, China *Science* **294** 2345–8

Wanner H 2021 Late-Holocene: cooler or warmer? *Holocene* **31** 1501–6

Warde P 2015 Global crisis or global coincidence? *Past Present* **228** 287–301

Warde P 2018 *The Invention of Sustainability: Nature and Destiny, C.1500–1870* (Cambridge: Cambridge University Press)

Webb J L A 1995 *Desert Frontier: Ecological and Economic Change along the Western Sahel 1600–1850* (Madison, WI: University of Wisconsin Press)

Webster D 2012 *The Classic Maya Collapse the Oxford Handbook of Mesoamerican Archaeology* ed D L Nichols and C A Pool (Oxford: Oxford University Press) pp 324–34

Weinberger V P, Quiñinao C and Marquet P A 2017 Innovation and the growth of human population *Phil. Trans. R. Soc.* ***B*372** 20160415

Weiss H and Bradley R S 2001 What drives societal collapse? *Science* **291** 609–10

Weiss H, Courty M A, Wetterstrom W, Guichard F, Senior L, Meadow R and Curnow A 1993 The genesis and collapse of third millennium North Mesopotamian civilization *Science* **261** 995–1003

Weiss H 2017 4.2 ka BP megadrought and the Akkadian collapse *Megadrought and Collapse: From Early Agriculture to Angkor* ed H Weiss (New York: Oxford University Press) ch 3, pp 93–160

Weninger B, Alram-Stern E, Bauer E, Clare L, Danzeglocke U, Jöris O, Kubatzki C, Rollefson G, Todorova H and van Andel T 2006 Climate forcing due to the 8200 cal yr BP event observed at Early Neolithic sites in the eastern Mediterranean *Quat. Res.* **66** 401–20

White S 2011 *The Climate of Rebellion in the Early Modern Ottoman Empire* (New York: Cambridge University Press)

White S 2014 Animals, climate change, and history *Environ. Hist.* **11** 319–28

White S 2017 *A Cold Welcome: The Little Ice Age and Europe's Encounter with North America* (Cambridge, MA: Harvard University Press)

White S, Brooke J and Pfister C 2018a Climate, weather, agriculture, and food *The Palgrave Handbook of Climate History* ed S White, C Pfister and F Mauelshagen (New York: Springer) pp 331–53

White S and Pei Q 2020 Attribution of historical societal impacts and adaptations to climate and extreme events: integrating quantitative and qualitative perspectives *Past Glob. Changes* **28** 44–45

White S, Pfister C and Mauelshagen F 2018b *The Palgrave Handbook of Climate History* (New York: Springer)

Wickman T M 2018b *Snowshoe Country : An Environmental and Cultural History of Winter in the Early American Northeast* (Cambridge: Cambridge University Press)

Wickman T 2015 "Winters embittered with hardships": severe cold, wabanaki power, and english adjustments, 1690–1710 *William Mary Q.* **72** 57–98

Wickman T 2018a Narrating indigenous histories of climate change in the Americas and Pacific *The Palgrave Handbook of Climate History* ed S White, C Pfister and F Mauelshagen (New York: Springer) pp 387–411

Wicks K and Mithen S 2014 The impact of the abrupt 8.2 ka cold event on the Mesolithic population of western Scotland: a Bayesian chronological analysis using 'activity events' as a population proxy *J. Archaeol. Sci* **45** 240–69

Widgren M 2012 Climate and causation in the Swedish Iron Age: learning from the present to understand the past *Geografisk Tidsskrift-Dan. J. Geogr.* **112** 126–34

Willcox G, Buxo R and Herveux L 2009 Late Pleistocene and early Holocene climate and the beginnings of cultivation in northern Syria *Holocene* **19** 151–8

Willcox G, Fornite S and Herveux L 2008 Early Holocene cultivation before domestication in northern Syria *Veg. Hist. Archaeobot.* **17** 313–25

Williams M 2021 *When the Sahara Was Green: How Our Greatest Desert Came to Be* (Princeton, NJ: Princeton University Press)

Williamson F 2020 The "cultural turn" of climate history: an emerging field for studies of China and East Asia *WIREs Clim. Change* **11** e635

Wilson A 2008 Boltzmann, Lotka and Volterra and spatial structural evolution: an integrated methodology for some dynamical systems *J. R. Soc. Interface* **5** 865–71

Wilson R *et al* 2016 Last millennium northern hemisphere summer temperatures from tree rings: part I: the long term context *Quat. Sci. Rev.* **134** 1–18

Windler G, Tierney J E, DiNezio P N, Gibson K and Thunell R 2019 Shelf exposure influence on Indo-Pacific Warm Pool climate for the last 450 000 years *Earth Planet. Sci. Lett.* **516** 66–76

Wisner B 2004 *At Risk: Natural Hazards, People's Vulnerability, and Disasters* (London: Routledge)

Workman L, Akcay N, Reeves M and Taylor S 2018 Blue eyes keep away the winter blues: is blue eye pigmentation an evolved feature to provide resilience to seasonal affective disorder *OA J. Behav. Sci. Psychol.* **1** 180002

Wu Q *et al* 2016 Outburst flood at 1920 BCE supports historicity of China's Great Flood and the Xia dynasty *Science* **353** 579–82

Xoplaki E *et al* 2018 Modelling climate and societal resilience in the Eastern Mediterranean in the last millennium *Hum. Ecol.* **46** 363–79

Xu A, Yang L E, Yang W and Hillman A L 2019 Resilience of the human-water system at the southern Silk Road: a case study of the northern catchment of Erhai Lake, China (1382–1912) *Socio-Environmental Dynamics along the Historical Silk Road* ed L E Yang, H Bork, X Fang and S Mischke (Cham: Springer) pp 325–58

Yang L E, Bork H R, Fang X, Mischke S, Weinelt M and Wiesehöfer J 2019 On the paleo-climatic/environmental impacts and socio-cultural system resilience along the Historical Silk Road *Socio-Environmental Dynamics along the Historical Silk Road* ed L E Yang, H Bork, X Fang and S Mischke (Cham: Springer) pp 3–22

Zhang D D, Jim C Y, Lin G, He Y-Q, Wang J J and Lee H F 2006 Climatic change, wars and dynastic cycles in China over the last millennium *Clim. Change* **76** 459–77

Zhang D D, Lee H F, Wang C, Li B, Pei Q, Zhang J and An Y 2011 The causality analysis of climate change and large-scale human crisis *Proc. Natl Acad. Sci.* **108** 17296–301

Zhang D D, Pei Q, Fröhlich C and Ide T 2019 Does climate change drive violence, conflict and human migration? *Contemporary Climate Change Debates* ed M Hulme (London: Routledge) pp 51–64

Zhang H *et al* 2021 Collapse of the Liangzhu and other Neolithic cultures in the lower Yangtze region in response to climate change *Sci. Adv.* **7** eabi9275

Zhang S, Pei Q and Zhang D D 2022 A quantitative analysis of the relationship between climate change and war along the Silk Road regions during the Little Ice Age *Quat. Sci.* **1** 250–60

Zhang Z, Tian H, Cazelles B, Kausrud K L, Bräuning A, Guo F and Stenseth N C 2010 Periodic climate cooling enhanced natural disasters and wars in China during AD 10–1900 *Proc. R. Soc.* B **277** 3745–53

Zhong Y, Miller G, Otto-Bliesner B, Holland M, Bailey D, Schneider D and Geirsdottir A 2011 Centennial-scale climate change from decadally-paced explosive volcanism: a coupled sea ice-ocean mechanism *Clim. Dyn.* **37** 2373–87

Zilberstein A 2016 *A Temperate Empire: Making Climate Change in Early America* (Oxford: Oxford University Press)