Archaeology, rapid climate changes in the Holocene, and adaptive strategies

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ABSTRACT - *The article presents the concepts of repeating cycles of rapid climate variability in the Holocene, including rapid cooling cycles, cold events, ice-rafting events, and rapid climate change recorded in palaeoclimate archives. It also discusses the concepts of adaptation strategies embedded in the catastrophic scenarios of collapse on the one hand, and panarchy, resilience, and adaptation cycle on the other,* i.e. *the processes of transforming social hierarchical structures into dynamic, adaptive entities. In the rapid climate change series we focus on the 9.2 ka and 8.2 ka climate events associated with the Neolithisation process and the transition to farming. The 5.9 IRD event and/or period of rapid climate change from 6000–5200 cal yr BP are associated with the cultural, economic, and demographic collapse of the Early Neolithic Linear Pottery culture in central and western Europe. We also discuss the triad of recent weakening of North Atlantic ocean circulation, decreased solar activity, and the hypothesised transition to a cold period, the well-known historical scenario associated with the transition to Little Ice Age between 1450 and 1850.*

KEY WORDS – *Holocene; archaeology; rapid climate changes; adaptation strategies; 8.2 ka climate event; Neolithisation; Little Ice Age*

Arheologija, hitre klimatske spremembe v holocenu in prilagoditvene strategije

IZVLEČEK – *V članku predstavljamo koncepte ponavljajočih se nizov hitrih podnebnih sprememb v holocenu, vključno z nizi hitrega ohlajanja, hladnimi dogodki, dogodki s plavajočim ledom in nenadnimi podnebnimi spremembami, zabeleženimi v paleoklimatskih arhivih. Predstavljamo in analiziramo tudi koncepte prilagoditvenih strategij, vgrajenih v katastrofične scenarije kolapsa na eni strani ter panarhije, odpornosti in prilagoditvenega cikla na drugi strani, tj. procese transformacije družbenih hierarhičnih struktur v dinamične, prilagodljive entitete. V seriji hitrih podnebnih sprememb se osredotočamo na podnebne dogodke 9,2 ka in 8,2 ka, povezane s procesom neolitizacije in prehodom na poljedelstvo. Dogodek 5.9 IRD in/ali obdobje hitrih podnebnih sprememb od 6000–5200 kal pr. n. št. je povezano s kulturnim, gospodarskim in demografskim propadom zgodnje neolitske kulture linearne keramike v srednji in zahodni Evropi. Omenjamo tudi triado nedavne oslabitve cirkulacije severnoatlantskega oceana, zmanjšane Sončeve aktivnosti in domnevnega prehoda v hladno obdobje, ki je dobro znan zgodovinski scenarij, povezan s prehodom v malo ledeno dobo med leti 1450 in 1850.*

KLJUČNE BESEDE – *holocen; arheologija; nenadne podnebne spremembe; prilagoditvene strategije; 8.2 ka klimatski dogodek; neolitizacija; mala ledena doba*

Introduction

In current discussions* of present climate anomalies and predictions, past climate variability is often overlooked. On the other hand, in archaeology the rapid climate changes of the past have not been properly contextualized or adequately conceptualized, and have often been simplistically and directly associated with the collapse of civilizations. In our paper we discuss the evolution of related concepts and interpretations, the causes of rapid climate changes and subsequent human adaptations during the last 12 000 years. Palaeoclimate archives reveal a succession of periods of varying length with cooling and droughts, warm periods, and regional heavy rainfall events. They include the well-known 8.2 ka and 4.2 ka events, the Late Antique Ice Age, the Little Ice Age, and the intervening Mediaeval Warm Period. In archaeological studies, these events are associated with global environmental catastrophes and collapses (economic, demographic, cultural, political) of cultures in prehistory and later civilizations. More recent interdisciplinary explanations have shifted the focus from a global framework to regional climate activities and from collapse to other adaptation strategies.

The first interpretations linking climate change to civilizational and cultural developments emerged in the early 20th century in the context of geographical, climatological, and archaeological studies. Sudden periods of drought and aridity were recognized as climatic and environmental factors that were associated with the catastrophic scenarios that afflicted Egyptian, Mesopotamian, and Indian civilizations, as well as with the invasion of Europe by nomadic peoples from Central Asia (*Huntington, Simpson 1926; Brooks 1926*). According to the adaptation scenario known as the oasis theory, climate determined the development of economic strategies, including the cultivation of plants and the domestication of animals, which were followed by agricultural development and cultural evolution (*Childe 1928*).

The catastrophe scenarios were recently replaced by the resilience and adaptive capacity scenarios, which include a society's ability to "*absorb energy and to redirect or to convert it, without losing the fundamental features and shape of the system as a whole*" and to adapt "*to actual or expected climate and its effects, in order to moderate harm or exploit bene-*

ficial opportunities" (*Degroot* et al. *2021.543*). The United Nations Intergovernmental Panel on Climate Change (IPCC) has played a key role in contextualizing and promoting both concepts (*Matthews 2018*). The concept of resilience is used in very different scientific fields and contexts. It first appeared in the psychology of the individual and then spread and evolved in interdisciplinary approaches in the environmental sciences, human sciences and humanities (see below for details). The term is often understood as the opposite of vulnerability, namely, the susceptibility of a social unit to existential threats from disturbances that may lead to its dissolution or destruction (see *van Bavel* et al. *2020*). However, Martin Endreß, Lukas Clemens, and Benjamin Rampp (*2020.1*) suggested that resilience and vulnerability can be simultaneously conceptualized as complementary – vulnerability is a necessary condition for resilience, and *vice versa*.

Toward the end of the 20th century, climatologists working on the Cooperative Holocene Mapping Project (COHMAP) introduced the long-term climate change model, which covers the last 18 000 years. Using radiocarbon dated proxy data (water levels in lakes, pollen in lakes and plankton in marine sediments, changes in the height and area of ice sheets), the project documented global climate changes at 3000-year intervals. COHMAP concluded that these intervals were caused by changes in cosmic rays and decreased and consequently altered atmospheric air circulation on Earth (*COHMAP members 1988*). The first change, the Holocene interval between 13 000 and 10 000 years BP, was linked to the Neolithic Revolution and the transition to farming in the Middle East. It was seen as human beings' first response to "*a unique sequence of climatic events*" (*Wright 1993.466*).

In the 21st century the INTIMATE Project Group (INTegration of Ice-core, MArine, and TErrestrial records) and the Subcommission on Quaternary Stratigraphy (SQS) with the International Commission on Stratigraphy (ICS) suggested that two rapid climate change events – the 8.2 ka event and 4.2 ka event – represent the boundaries between early and mid-Holocene, and mid- and late Holocene. Using chemical proxy data (changes in the ratio of stable oxygen isotopes $^{18}O/^{16}O$ and water evaporation D/H), the sudden and substantial cooling and drought of the first event is best documented in the Greenland ice core NGRIP1,

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but is also documented globally in lake pollen and deep-sea plankton sediment records, as well as in cave speleothems. The second is not recorded in the ice core, but is well documented across all continents in pollen, lake diatom and deep-sea planktonic records, cave speleothems and altered monsoon cycles (*Lachniet 2009; Walker* et al*. 2012; 2018; Lowe, Walker 2015.428–433;* see also *Moossen* et al. *2015*).

In archaeological studies (details are below), the relations between prehistoric cultures and climate changes were determined using various theoretical standpoints and interpretative contexts, even ones that were mutually exclusive. First, the determinist model of unilinear cultural evolution and diffusion saw any change in human behavioural patterns, economic or technological development or cultural trajectories as directly associated with climate and environmental changes. On the other hand, there was also the categorical denial of the environment as a possible cause of cultural change, and any attempt to link the two was seen as environmental determinism (*Jones* et al. *1999*). Similarly, processual archaeology (New Archaeology) saw the development of prehistoric societies as entirely dependent on successfully adapting to climate and environmental changes (*Binford 1968; Tainter 1988*). Later, post-processual archaeology found studies of human-environment interaction to be determinist. This approach, according to post-processual archaeology, was based on the assumption that external environmental processes were the main contributing factor to cultural change, which does not acknowledge the historic contingency of human activity (*Hodder 1982; 2000; Ingold 2000;* for an example of the transition to farming, see *Gremillion* et al. *2014*). More recent interdisciplinary approaches are often limited to temporal correlations between rapid climate change and archaeological cultural change (*Rohling* et al. *2019*), and emphasize the continuum of interaction between cultural systems and environmental processes, *i.e.* environmental and cultural co-evolution (*e.g.,* the concepts of a cultural niche and the archaeology of climate changes) (*Izdebski* et al. *2016; Rockman, Hritz 2020; Rick, Sandweiss 2020; Burke* et al. *2021*).

Replacing long-term climate changes with the rapid changes

In palaeoclimatology, models of long-term changes have been replaced by those focused on rapid changes with substantial decreases in temperature,

including rapid cooling cycles, (as well as ice-rafting events), rapid climate change, and cold events. Gerard Bond *et al.* (*1997; 1999*) introduced the concept of cooling cycles as eight repeating cycles of rapid cooling. These were characterized as climate events associated with depositing ice-rafted debris, so-called IRD events, which occurred along the North Atlantic in the interval of ~1470 ± 500 years. Bond's group associated these with influxes of large quantities of cold glacial water, impacting the circulation of the North Atlantic Gulf Stream. These influxes were documented using stone debris transferred by icebergs broken off from the Arctic ice caps and deposited in deep-sea sediments. Using radiocarbon dating of planktonic foraminifer shells from two North Atlantic deep-sea cores, the nine IRD events in the Holocene were dated in the core VM 29-191 in the following sequence: 12.5, 11.1, 10.3, 9.5, 8.2, 5.9, 4.3, 2.8 and 1.4 cal 10^3 yr BP (*Bond* et al. *1997.Fig. 2.1*). The increased influxes of glacial meltwater into the ocean were associated predominantly with periods of low solar activity (*Bell 1971; Bond* et al. *2001*). However, new deep-sea cores in the eastern and western Mediterranean have not confirmed Bond's cycle model. Rapid cooling occurred in an interval of 2300–2500 years in the eastern Mediterranean (*Rohling* et al. *2002a*), and in intervals of 1300, 1515, 2000 and 5000 years in the western (*Rodrigo-Gámiz* et al. *2014*). These changes were exclusively associated with cycles of higher or lower solar activity and ultraviolet radiation, as well as changes in the thickness of the ozone layer, which led to temperature changes in the lower parts of the stratosphere and consequently to occasional outbreaks of polar air masses toward the south of the northern hemisphere. The consequences were increased activity of the Siberian anticyclone and the overflow of Arctic air during the winter and spring months in the Mediterranean. Rapid cooling has been documented in three deep-sea cores (south Adriatic Sea IN68-9, south-east Aegean Sea LC2 and the LC31 core west of Cyprus) in a sequence of cold events 3.0–3.8 (LC21 only), 5.8–6.7, 7.9–8.6, (9.5–10.0, Adriatic only), 11.0–13.4, and (poorly defined) 16–18 kyr cal BP (*Rohling* et al. *2002b.40*). A concurrent sequence of is also documented in the Adriatic Sea (*Siani* et al. *2013*).

The model of rapid climate changes was developed by Paul A. Mayewski *et al.* (*2004*; see also *Anderson* et al. *2007*). Using more than fifty palaeoclimate archives, they modelled a series of six sudden, sharp, and rapid global temperature declines (rapid climate change or

RCC) that were repeated over periods of 2800–2000 and 1500 years. In the Western Mediterranean, intervals of 1300, 1515, 2000, and 5000 years were later included in the model, as mentioned above (*Rodrigo-Gámiz* et al. *2014*). They are embedded in radiocarbon calendar series between 9000–8000, 6000–5000, 4200–3800, 3500–2500, 1200–1000 and after 600 cal yr BP or cal b2k. The first cooling in this series is known as the 8.2 ka event (*Alley* et al. *1997*) or the 8200 yr BP event (*Mayewski* et al. *2004.252*). It was caused by a large influx of glacial meltwater into the North Atlantic. All other rapid climate changes are associated with changes in solar activity, radiation, and solar irradiance. They are all characterized by cooling of the northern hemisphere, tropical droughts, and changes in atmospheric circulation.

A contrasting pattern has been documented in the Alps and part of central Europe in the latitudinal belt between 43° and 50° north. Pollen deposits, palaeohydrological and other proxy data from lake sediments indicate a particularly wet period at the time of the first climate event. Lake water levels show fluctuations and a sequence of rising, falling, and rising again (*Magny* et al. *2003*). A similar sequence in the Mediterranean has also been documented in relation to the 4.2 ka event. Humid periods and high lake levels during *c.* 4300–4100 and 3950–3850 BP were interspersed with periods of severe cooling and drought with low lake levels between *c.* 4100–3950 BP, although it should be noted that this activity was regional and heterogeneous (*Magny* et al. *2009a*; *2012; Bini* et al. *2019*).

In their contribution to the IPCC's Fifth Assessment Report a few years ago, Working Group I replaced the word 'rapid' with 'abrupt' in relation to climate change. They defined this as a "*large-scale change in the climate system that takes place over a few decades or less, persists (or is anticipated to persist) for at least a few decades and causes substantial disruptions in human and natural systems*" (*Stocker* et al. *2013.1448*). These changes are apparent in the collapse of individual climate system components, such as the collapse of the Atlantic meridional overturning circulation, glacier collapse, permafrost carbon release, methane clathrate release, the disappearance of tropical and boreal forests, the disappearance of summer Artic sea ice, prolonged droughts, and the collapse of monsoon circulation (*Stocker* et al. *2013.1114–1118, Tab. 12.4*).

Related to Bond's series of rapid cooling events is a model of cold events, a century-long set of global climate anomalies. The model is based on analysis of proxy data on temperature, precipitation, and glacial dynamics preserved in various palaeoclimatic archives on land, in lakes, in the deep sea, and in ice cores (*Wanner* et al. *2008; 2011; 2012*). During the Holocene, six events of sudden temperature decline have been documented. The first, the 8.2 kyr BP event, took place 8300–8100 years ago. However, it is worth noting that the estimated temperature declines related to this event occurred in different regions over a longer period of 400 to 600 years (*Rohling, Pälike 2005*). Three more follow in prehistory: the second event 6.5.–5.9, the third 4.8–4.5 and the fourth 3.3–2.5 took place 6400–6200, 4800–4600 and 2800–2600 years ago. The fifth event 1.75–1.35 and sixth event 0.7–0.15 occurred 300–600 and 1200–1800 years ago, and are associated with the so-called Dark Ages and Migration Period, and the Little Ice Age, respectively (*Wanner* et al. *2011*).

In a parallel study, Shaun A. Marcott *et al.* (*2013*) used 73 palaeoclimate archives in the northern and southern hemispheres to track global temperature trends over the past 11 300 years. A warming phase in the early Holocene (10 000–5000 years BC) was followed by a cooling at ∼0.7°C in the middle (<5000 years BC) and late Holocene, reaching its lowest point during the Little Ice Age about 200 years ago. Two years later, Heiko Moossen *et al.* (*2015*) noted a similar North Atlantic trend of declining land and ocean surface temperatures. Terrestrial temperatures were highest in the early Holocene (10.7–7.8 kyrs BP), while at sea level they were highest in the mid-Holocene due to the influx of glacial meltwater (7.8–3.2 8 kyrs BP) (Fig. 1). They identified two warm periods in the early Holocene between ∼8.9–∼8.5 kyrs BP and ∼8.1–∼7.9 kyrs BP, both coinciding with periods of intense solar activity. The 8.2 ka event is unfortunately poorly documented in the core of the Danish peninsula Vestfirdir in this context. Two periods of rapid warming were also noted in the mid-Holocene at ∼7.6 and ∼7.3 kyrs BP. In the first, sea level temperatures increased by ∼5°C (0.5°C per decade), while in the second period temperatures increased by ∼4°C and persisted for 1400 years. The temperature increases were correlated with Bond cycles 5 and 4. Between ∼5.8 and ∼3.2 kyrs BP there was a period of decreasing temperatures and new glaciation. In the late Holocene (∼3.2–∼0.3 millennia ago), two warm and two cold periods were documented, the first between
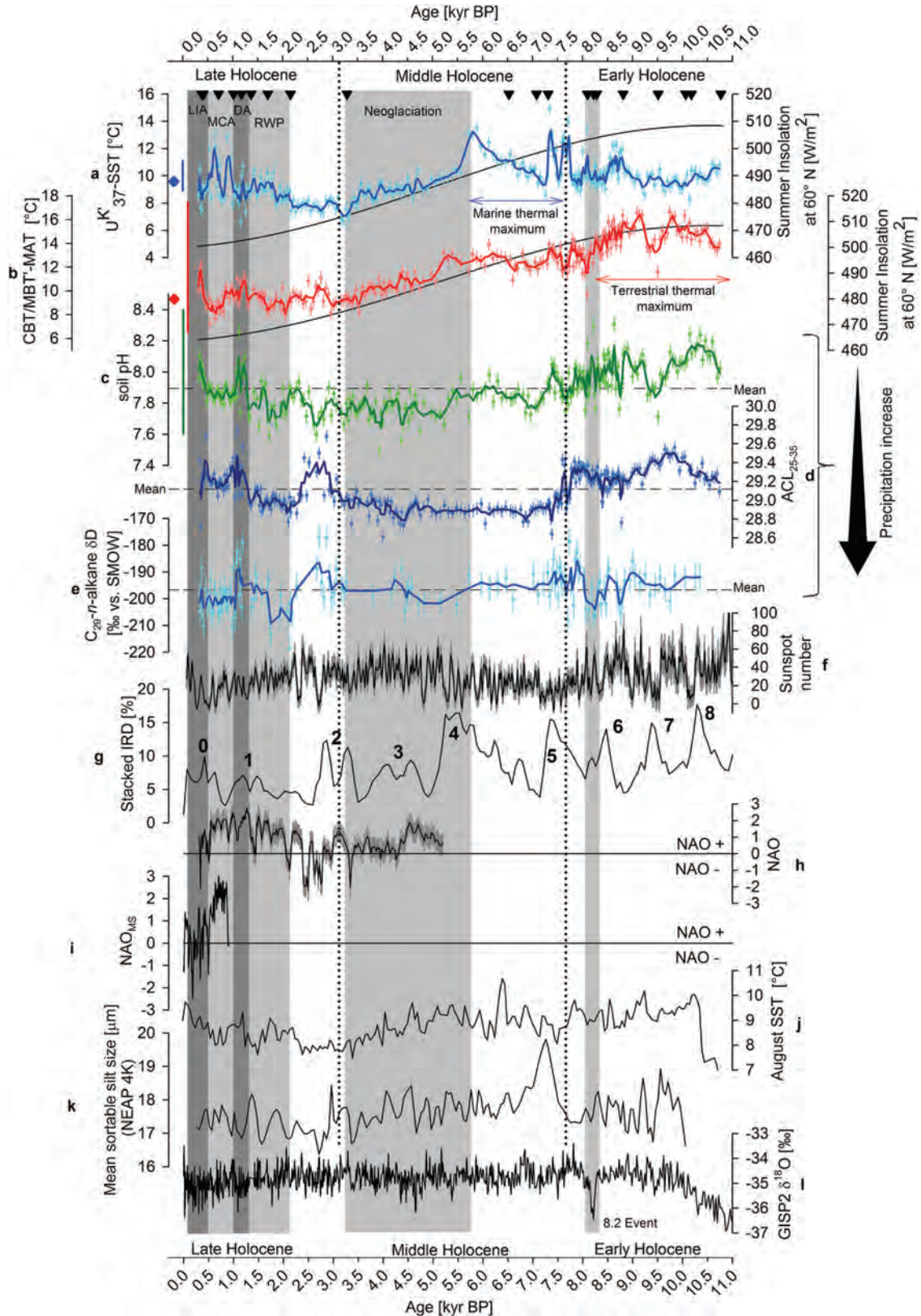
Fig. 1. A comparison of the Icelandic climate records with other North Atlantic palaeoclimate records. The Little Ice Age (LIA), Mediaeval Climatic Anomaly (MCA), Dark Ages (DA), Roman Warm Period (RWP), neoglacial period, and 8.2 ka event are highlighted in shades of grey. Reprinted from Moossen et al. 2015. North Atlantic Holocene climate evolution recorded by high-resolution terrestrial and marine biomarker records. Quaternary Science Reviews 129: 115, Fig.6. Reprinted with permission from Elsevier. For an explanation of the figure legend, see https://doi.org/10.1016/j.quascirev.2015.10.013.

~2.2–~1.3 and ~1.1–~0.5 kyrs BP, and the second between ~1.3–~1.1 and ~0.5–~0.3 kyrs BP. The former was associated with the Roman Warm Period (RWP) and the latter with the Early Middle Ages (Dark Ages). A more recent Holocene palaeotemperature database is available in Darrell Kaufman *et al.* (*2020*) as well as online (*Temperature 12k Database, www. ncdc.noaa.gov/paleo/study/27330, https://doi.org/ 10.25921/4ry2-g808*).

Corresponding with the rapid climate changes and the cold events is a sequence of fifteen events with higher lake levels documented in 26 lakes in the northern French Prealps, the Jura and the Swiss Plateau. Radiocarbon dates determined the following sequences: 11 250–11 050, 10 300–10 000, 9550–9150, 8300–8050, 7550–7250, 6350–5900, 5650–5200, 4850–4800, 4150–3950, 3500–3100, 2750–2350, 1800–1700, 1300–1100, 750–650 years BP (*Magny 2004; Magny, Haas 2004; Magny* et al. *2006; 2009b*).

Periods of high precipitation have been documented in the central Mediterranean at *c.* 10 200, 9300, 8200, 7300, 6200, 5700–5300, 4800, 4400–3800, 3300, 2700–2300, 1700, 1200 and 300 years BP. In the middle Holocene a contrasting pattern of precipitation regimes is notable, with wet winters and dry summers documented north of the parallel 40° north, and wet winters and wet summers documented south of it. In the late Holocene the pattern reverses (*Magny* et al. *2012; 2013; Peyron* et al. *2013*).

Rapid climate changes in archaeological studies

In archaeology a variety of theoretical approaches and interpretive contexts have been used to establish links between prehistoric cultures and climate changes (a detailed review and examples follow below, see also *Trigger 1971; 1996*). From the beginning, these links were embedded in a deterministic view of unidirectional cultural evolution and diffusion, in which any change in human behaviour patterns, economic or technological developments, and cultural trajectories was seen as directly correlated to climate and environmental changes (*Clark 1936; Childe 1958; Shennan 2005*). Similarly, the New Archaeology viewed the development of prehistoric societies as entirely dependent on how successfully they adapted to such changes (*Binford 1968; Tainter 1988*). In contrast, post-processual archaeology assumes that it was human activities that triggered such changes, including changes in the natural environment (*Hodder 1986; Tilley 1994*).

Similarly, interdisciplinary studies have consistently associated the dynamics of archaeological landscape change and cultural change during the Holocene with climate and environmental change at regional and global scales (reviewed in *Berglund 2003; Brown, Bailey, Passmore 2015*). The correlations were created by ^{14}C dating of archaeological settlement contexts and palaeoclimate archives. The latter are preserved in a variety of environments: glacial (ice cores), geological (marine and terrestrial), and biological. A key element in these archives is the proxy data on past climate fluctuations, including stable oxygen and carbon isotopes, dust particles, various gas concentrations in air bubbles in ice; glacial and periglacial deposits, surface erosion, palaeosols, volcanic eruptions; biochemical markers in animal and plant plankton fossils, stable oxygen and carbon isotopes in deep-sea sediments and sapropel deposits; pollen and plant macrofossil remains in marine and terrestrial sediments, diatoms, ostracods, insects, and stable isotopes in lake sediments; stable oxygen and carbon isotopes in dripstone; the circumference of tree rings and the stable carbon isotopes they contain; and stable carbon isotopes deposited in fossil cereal grains. The proxy data allow the reconstruction of long prehistoric sequences of temperature and precipitation periods and shifts, solar irradiance and associated climate fluctuations, changes in sea and lake levels, and changes in vegetation cover (*Bradley 1999; Briffa 2000; Sachs* et al. *2000; Barber* et al. *2004; Jones, Man 2004; Magny* et al. *2004; Marino* et al. *2009; Steinhilber* et al. *2012; Riehl* et al. *2014*).

The first comprehensive correlation between rapid climate changes, archaeological cultures and past cultural dynamics on a global scale appeared in a palaeoclimate interpretative context. It was grounded by statistical analyses of anomalies in the distribution of 815 radiocarbon dates related to pollen distribution, sea level changes, and peat accumulations in palaeobotanical records, and 3700 ^{14}C dates associated with 155 archaeological settlement and cultural sequences (*Wendland, Bryson 1974; Bryson 1988*).

Deterministic catastrophe interpretations, which assumed rapid climate change as the cause and demographic and civilizational collapse and dark periods as the consequences, remained dominant. The best known examples are the end of the Fifth and Sixth Dynasties in Egypt, the invasion of Egypt by the Sea Peoples in 1177 BC; the end of Mycenaean Greece, the decline of the Hittite and Akkadian empires, the end

of the Third Dynasty of Ur in Mesopotamia (*Carpenter 1966; Bell 1971; Bryson* et al. *1974; deMenocal 2001; Cline 2021*). These were all associated with sudden cooling and drought, and the desertification of the regions. The legitimacy of the perception of catastrophic events was based on the postulate that the dark ages and climate fluctuations were a factor in history (*Bell 1971*).

Much attention has been focused on the Tell Leilan event, the gap in the settlement sequences in tell sites (Tell Leilan, Tell Brak, Tepe Garwa) in northern Mesopotamia about 2200 years ago that marks a rapid change in climate, desertification of the region, the collapse of the irrigation-based economy, and the resulting collapse of the Akkadian Empire (*Weiss* et al. *1993; Courty, Weiss 1997; Weiss, Bradley 2001; Cullen* et al. *2000; deMenocal 2001.669*). A similar scenario was assumed for the collapse of Classic Maya culture (*Hodell* et al. *1995; deMenocal 2001.670; Haug* et al. *2003*).

However, Karl W. Butzer (*1972; 1975; 2012; Butzer, Endfield 2012*) pointed out the conceptual weakness and interpretive limitations of the deterministic approach. As an alternative to the postulate of climate as the sole cause of the collapse of past civilizations, he proposed an interdisciplinary approach, which he called cultural ecology, emphasizing pre-industrial societies still affected the ecological balance in their regions, leading to an economic, demographic and cultural slippage that resulted not in collapse but in cultural and economic adaptation to the new environment. A similar view is also found in the French Annales approach, where it is emphasized that the impacts of climate change on past societies were indirect and hardly noticeable. The Little Ice Age and the outbreak of the plague at the end of the 16th century, as well as the widespread crisis in 17th century Europe, were cited as examples. Le Roy Ladurie (*1971.17*) claimed that famines, pandemics, migrations, insufficient food production, and high food costs are not and cannot be facts which are strictly climatic. Crawford S. Holling (*1973*), on the other hand, introduced to ecology the concept of resilience, emphasizing that all natural systems have the capacity to absorb environmental and climatic disturbances without changing dramatically. However, resilience is limited, and when changes reach a critical point the system will transform and adapt to the new conditions.

A paradigm shift

In the mid-1970s the palaeoclimatologist Wallace S. Broecker (*1975*) was already warning about pronounced global warming, while the palaeo-oceanographer John Imbrie and his daughter Katherine Palmer Imbrie (*1979*) were predicting that the use of fossil fuels would lead to a super-interglacial age, unlike anything experienced in the last million years. With the publication of the IPCC's first report and assessment of the state of the climate system, including projected future changes, in 1990, acceptance of the global warming scenario increased rapidly. The shift in paradigm from rapid global cooling to global warming was based on new proxy data, and the correlation between past gas concentrations in the atmosphere and the climate changes in ice and deep-sea palaeoclimate archives, the application of General Circulation Models (GCM) to atmosphere and ocean circulation, and the increase in global atmosphere temperatures in the last century (*Chambers, Brain 2002; Alley* et al. *2003*). The IPCC's fourth report, comprised of the working reports of three different work groups (the second dealt with impacts on the environment and human adaptation to climate change), emphasized that the growing concentrations of greenhouse gases after 1750 were the consequence of human activity. Neither the concentrations of carbon dioxide (CO_2) or methane (CH_4) in the past 650 000 years, nor the concentrations of nitrous oxide (N_2O) in the past 16 000 years, have ever been as high as they are now (*Parry* et al. *2007; Bernstein* et al. *2008*). The increased concentrations of carbon dioxide and methane in 8000–5000 BC were linked to the Neolithic beginnings of agriculture, decreased forest areas in Europe, and the spread of rice fields and their irrigation systems in India and China (*Ruddiman 2003*).

In contrast, the rapid decline in average surface temperatures and salinity in the Labrador Sea water column that began in the second half of the 20th century remains a major challenge in predicting rapid cooling (*Lazier 1995; Dickson* et al. *2002*). The temperature and salinity declines indicate a weakening of the Atlantic Meridional Overturning Circulation (AMOC), which transports warm/cold water and low/high salinity water from one part to another (thermohaline circulation). This circulation is key to heat redistribution on our planet and, together with the atmospheric circulation (North Atlantic Oscillation, NAO; Arctic Oscillation, AO; and Mediterranean Oscillation, MO), has been a major influence on global climate vari-

ability in the past (see below). Changes in circulation have been associated with changes in solar activity (*Usoskin 2008; 2017; Usoskin* et al. *2016*), on the one hand, and rapid changes between warm and cold periods in the Younger Dryas (12 900–11 600 years BP) (*Rahmstorf 2002; Caesar* et al. *2021*), Medieval Climate Anomalies (*c.* 900–1300 AD), and the Little Ice Age (1450–1850 AD) (*Bradley* et al. *2003; Velasco Herrera* et al. *2015; Zharkova* et al. *2015; Fogtmann-Schulz* et al. *2021*), on the other.

It should be noted that glacial periods and interglacial periods are not uniformly cold or warm. The Greenland palaeoarchives indicate considerable climate variability and a succession of cold and warm periods, but also transitions that may have been so brief that they were overlooked in earlier studies. Such transitions can last decades or a century, as can warm periods followed by cold periods of several centuries or millennia. More than ninety events, *i.e.* climate oscillations and abrupt climatic events that relate well to stratigraphic and temporal boundaries in the proxy data, have been documented in three chronologically synchronized Greenland ice core records – NGRIP, GRIP, and GISP2 – dating back to 120ka b2k2 (*i.e.* 120 thousand years BP) with high stratigraphic and temporal resolution. All events occur in irregular succession, and 25 sudden and rapid transitions from cold to warm periods, which can last several decades, are particularly striking during the last glaciation. Temperatures range from 5°C to 16°C. Warm periods last from a century to several millennia, and temperatures decrease gradually. Cold periods are characterized by a more stable climate, and their duration is similar to that of warm periods (*Rasmussen* et al. *2014*). Macrofossil plant and animal remains in the Lena River delta on the Arctic Ocean and sediments from Kotokel Lake near Lake Baikal in Siberia confirm high annual temperatures during warm periods of the last ice age. Chironomidae larvae prove that summer temperatures were between 1.5°C and 3.5°C higher than today (*Tarasov* et al. *2021; Wetterich* et al. *2021*).

The sequences of Medieval Climate Anomalies (known as the Medieval Warm Period and Medieval Climatic Optimum) between 900 and 1300 AD and the Little Ice Age between 1450 and 1850 AD are also informative in the interpretative context of paleoclimatology, historical climatology, and regional paleoclimate modelling. Interpretations of the former rely on statistical analysis and reconstruction of past climate from proxy data, while the latter relates historical data and proxy data on a limited scale.

The collection of global proxy data and the regional reconstructions of rapid (decades-long) climate changes should also be mentioned (*Goose* et al. *2006; Ludwig* et al. *2019; Pfister* et al. *2018*), since changes at the global scale are not necessarily synchronous. Awareness of their short- and long-term impacts on society (*Mann 2012; Parker 2013; White* et al. *2018*) therefore remains as important as predicting trends in climate variability (*Jones, Osborn, Briffa 2001; Bradley* et al. *2003; National Research Council 2006; PAGES 2k Consortium; Neukom* et al. *2019*). Indeed, it is hypothesized that the trajectory from the Mediaeval Warm Period to the Little Ice Age was a global scenario that could be repeated in the present, since the past increase in global surface temperature was certainly not due to human activity in the pre-industrial period (*Lamb 1965; 1982*). The trajectory can also be described as a transition from settling and dairy farming in Greenland and Iceland during the Medieval Warm Period, to famines and plague epidemics in southeastern Europe during the Little Ice Age (*Xoplaki* et al. *2001; Mann 2002a*).

Recent paleoclimatological studies have focused on the asynchronicity of climatic events and the fact that average surface temperatures during the Middle Ages in the northern hemisphere were never as high as in the second half of the 20th century and early 21st century. The warmest period was between 950 and 1100, but temperatures at that time were between 0.1°C and 0.2°C below the average temperatures measured between 1961 and 1990 (*Jones* et al. *1998. 468–469*). The magnitude of warming today is global, but the Middle Age warm periods were asynchronous and regional. They occurred in the northern hemisphere between 830 and 1100, and between 1160 and 1370 in the southern. Similarly, the cooling and transition to the Little Ice Age occurred first in the Arctic, Europe, and Asia, and only later in North America and the southern hemisphere, as indicated by paleoclimate proxy data. The major climate fluctuations and the onset of the Little Ice Age on a global scale, with variations in solar magnetic activity, changes in atmospheric air circulation and ocean currents, and volcanic eruptions (*Mann* et al. *2008. 13255; PAGES 2k Consortium 2013.342*; see also *Bradley* et al. *2003; Wanner* et al. *2008*). A solar activity cycle immediately before the Wolf Minimum between 1260 and 1270 marks the beginning of the transition to a cold period.

We mentioned earlier the correlative processes of recent weakening of North Atlantic ocean circulation, decreased solar activity, and the hypothesised transition to a cold period (*Thompson, Wallace 2001; Rahmstorf 2002; Mörner 2015; Velasco Herrera* et al. *2015; Caesar* et al. *2018.195*). The triad contradicts the claims that "*[t]here is no impending little ice age*" (Ask NASA Climate 2020) and that "*[t]here were no globally synchronous multidecadal warm or cold intervals that define a worldwide Medieval Warm Period or Little Ice Age*" (*PAGES 2k Consortium 2013.339*). However, climate reconstructions of the past 2000 years based on palaeoclimate proxy data on surface temperatures (tree rings, pollen, corals, lake and marine sediments, ice cores, stalagmites, and historical data) at 511 sites in different regions of the world show "*a clear regional expression of temperature variability on the multidecadal to centennial scale, while a long-term cooling trend before the twentieth century is evident globally*" (PAGES 2k Consortium 2013.344).

Not to be overlooked is the critical commentary on the Intergovernmental Panel on Climate Change (UN) reports on climate trends in the 21st century published by a group of interdisciplinary researchers in the special volume titled *Pattern in Solar Variability, their Planetary Origin and Terrestrial Impacts* in the journal *Pattern Recognition in Physics* (*2013*; http://www.pattern-recogn-phys.net/special_issue2. html).

They wrote that "*[o]bviously, we are on our way into a new grand solar minimum. This sheds serious doubts on the issue of continued, even accelerated warming as claimed by the IPCC project*" (*Mörner* et al. *2013.206)*. The journal was discontinued a year later, in 2014, by the publisher Copernicus Publications for "*malpractice in scientific publishing*" (https:// www.pattern-recognition-in-physics.net/). It is noted that the co-editor of the journal was Sid-Ali Ouadfeul of the Algerian Petroleum Institute, the articles were considered scientifically questionable, and the editors corrupt. However, we have already entered a period of decreased solar activity known as the Modern Grand Solar Minimum, which will last from 2020 to 2053. It is believed to be similar to the Maunder Minimum associated with cold periods of the Little Ice Ages (*Mörner 2015; Zharkova 2020*).

The politicization of global warming, global warming models (including factors such as greenhouse gases,

tropospheric aerosols, solar and volcanic activity, and land use changes), and the global climate system are well presented in *The Palgrave Handbook of Climate History* (see *Brönnimann 2018; Oreskes* et al. *2018; Zorita, Wagner 2018; Zorita, Wagner, Schenk 2018*).

We have already mentioned that the Little Ice Age between 1450 and 1850 was not a uniform cold period. Large climatic variations are documented for the years 1675–1715 and 1780–1830. The largest are embedded between 1697–1708, in a period of extremely harsh climatic conditions and probably the coldest decade in the northern hemisphere during the last millennium. Average winter temperatures were 3–4°C and spring temperatures were 2°C lower than in the 20th century. Palaeoclimatological models of summer temperatures and dendrochronological data have shown that the summers of 1695, 1698, and 1699 were among the coldest in the northern hemisphere in the last 600 years. On the other hand, there were also extremely hot summers during this period, in 1707 and 1710. Long winters and frosts, as well as rainy summers and floods, posed many problems for agriculture. Snow, which lingered in the Balkans and eastern Mediterranean until late spring, made sowing impossible and caused the loss of winter cereals, while crops were destroyed by droughts, early hoarfrost, and autumn snow. Advancing glaciers covered several villages and pastures in the Alps. Fodder became scarce and many livestock perished at this time. Famines in the British Isles, Scandinavia, western and southeastern Europe, and the eastern Mediterranean caused several plague epidemics and had a major impact on demographic change (*Jones* et al. *1998; Briffa* et al. *1998; Luterbacher* et al. *2001; Slonosky* et al. *2001; Xoplaki* et al. *2001; Mann 2002b.504–509; Bradley* et al. *2003*).

The beginning and end of the Little Ice Age coincide with periods of low solar activity known as the Spörer Minimum (1440–1460) and Dalton Minimum (1809–1821). A period of great climate variability and extremely harsh climatic conditions in between coincides with the Maunder Minimum (1675–1715). Palaeoclimatologists have linked solar cycles and low solar activity to the weakening of the Atlantic Meridional Overturning Circulation (*Slonosky* et al. *2001; Rahmstorf 2002; Steinhilber, Beer 2011; Velasco Herrera* et al. *2015; Mörner 2015; Zharkova 2020; see also Mörner, Tattersall, Solheim 2013; Mörner* et al. *2013*), and altered atmospheric circulation (North

Atlantic, Arctic, and Mediterranean Oscillations). This relates to the fluctuation of atmospheric pressure and air mass movement between the Icelandic low-pressure area (Icelandic cyclone) and the Azores and Siberian high-pressure area (Azores anticyclone and Siberian anticyclone), which affect the climate in Eurasia, the Mediterranean, and the Arctic. Fluctuation indices describe the changes and differences in air pressure and intensity, as well as the direction of air mass movement in these areas. Positive North Atlantic Oscillation index values indicate that air pressure over the Atlantic and western Europe is higher than average. Westerly winds are stronger and moving northward. Temperatures are significantly higher and western Europe is wetter, while most of the Mediterranean experiences periods of decidedly dry weather. With a negative index, the westerly winds are weaker and the influence on the climate reverses. During the negative phase of the Arctic Oscillation, air pressure is higher than average over the Arctic and lower over the North Atlantic. Cold polar air moves south across the Mediterranean Sea to North Africa. These two phenomena are particularly pronounced in the cold part of the year (*Marshall* et al. *2001; Shindell* et al. *2001; Thompson, Wallace 2001*; *Wanner* et al. *2001; Dünkeloh, Jacobeit 2003; Toreti* et al. *2010; Roberts* et al. *2012; Tubi, Dayan 2013*).

We can see a similar climatic scenario the late Middle Ages. According to Bruce M. S. Campbell (*Campbell 2016*), it was embedded in the period 1270–1470 and had three key episodes. The first, between 1260/70 and 1220, was associated with the Wolf Solar Minimum and the end of strong solar activity and above-average global temperatures. The second, middle episode occurred between 1340 and 1370 and is characterized by greatly reduced solar activity, significantly narrower tree rings between 1342 and 1354, and severe cooling in the northern hemisphere with an influx of polar air southward, weakening monsoons and drought in South Asia, and stronger monsoons and floods in Africa. Similar climatic events continue in the third episode between 1370 and 1470, which partially coincided with the Little Ice Age and was characterized by high and low solar activity (the Chaucerian Maximum and the Spörer Minimum). Campbell has linked this triad to significant economic decline, the Hundred Years' War in western Europe, the collapse of the Eastern Roman Empire, the wars of conquest of the Ottoman Empire, the end of the Silk Road (an intercontinental economic, trade, technological, and cultural network and long-distance travel

route), famines, ectoparasites that decimated sheep and cattle herds, and plague epidemics in animals and humans. He characterized these processes as "*interactions between nature and society*" and called them "*the great transition*" (*O.c. 1*). He introduced the perception of a global historical trajectory where natural processes are the main triggers for demographic, economic, social, political, and cultural change. A year later, Geoffrey Parker (*2013*) also linked climate events and natural disasters in the 17th century, during the Little Ice Age, to global economic, health, demographic, and political crises. In this context it is also worth mentioning the connection between a cooling cycle in the Late Antique Little Ice Age of 536–660 and the Justinian Plague, the transformation of the Eastern Roman Empire, the migration of the Pannonian Avars and the Slavic peoples, the decline of the Sasanid Empire and the Eastern Turkic Khaganate, and the political upheavals in China (*Büntgen* et al. *2011; 2016*) (Fig. 2).

Concerns about human impact on the recent warming of the Earth's atmosphere and the growing knowledge of the frequency, rate, and extent of climate changes in the past led to a series of reflections on past environmental catastrophes and how humans responded to them. In this context, the catastrophe approach and the concept of collapse became very popular as a single-cause interpretive hypothesis, linking rapid cooling cycles, droughts, and floods to the collapses of earlier hunter-gatherer communities in southwest Asia, Bronze Age civilizations in the Aegean, eastern Mediterranean, and southwestern Asia, the Akkadian Empire in Mesopotamia, the Old Kingdom in Egypt, pre-Columbian Maya and Moche civilizations in Central and South America, and the Norse Greenland societies (*Arneborg* et al. *1999; Cullen* et al. *2000; Gill 2000; deMenocal 2001; Van Buren 2001; Hodell* et al. *2001; 2005; Williams 2002; Haug* et al. *2003; Stanley* et al. *2003; Dillehay* et al. *2004; Fagan 2004; Diamond 2005; Rodning 2010; Parker 2013; Brooke 2014; Campbell 2016; Kaniewski, Van Campo 2017; Bar-Yosef, Bar-Matthews, Ayalon 2017*). Jared Diamond (*2005.3,6,20*) was the only one of these authors to point out the complexity of these processes and the overlooked fact that examples of past civilization collapse (population decline and/or decline in political, economic, and social complexity over a significant area over an extended period of time) were not necessarily the cases of true ecological collapse, but of collapse caused by unsustainable survival strategies, poor management of natural resources, and ecosystem degradation.

Conceptualization adaptation strategies

Collapse is the most radical adaptation strategy used by past societies (*Tainter 2000a.332*). Using systems theory and catastrophe theory, Colin Renfrew (*Renfrew 1979a; 1979b*) defined it as an allactic type of cultural change characterized by two developmental trajectories: anastrophe and catastrophe. The former is associated with an increase in organizational complexity and centralization, the emergence of new bureaucratic and other forms of power structures, and consequently the increased use of economic resources. The latter relates to the disintegration of centralized and socially structured complex societies and their regressive reformulation into fragmented and disjointed chiefdoms and tribal communities. In both cases, the key elements are bifurcations, points of separation where the system chooses its own trajectory,
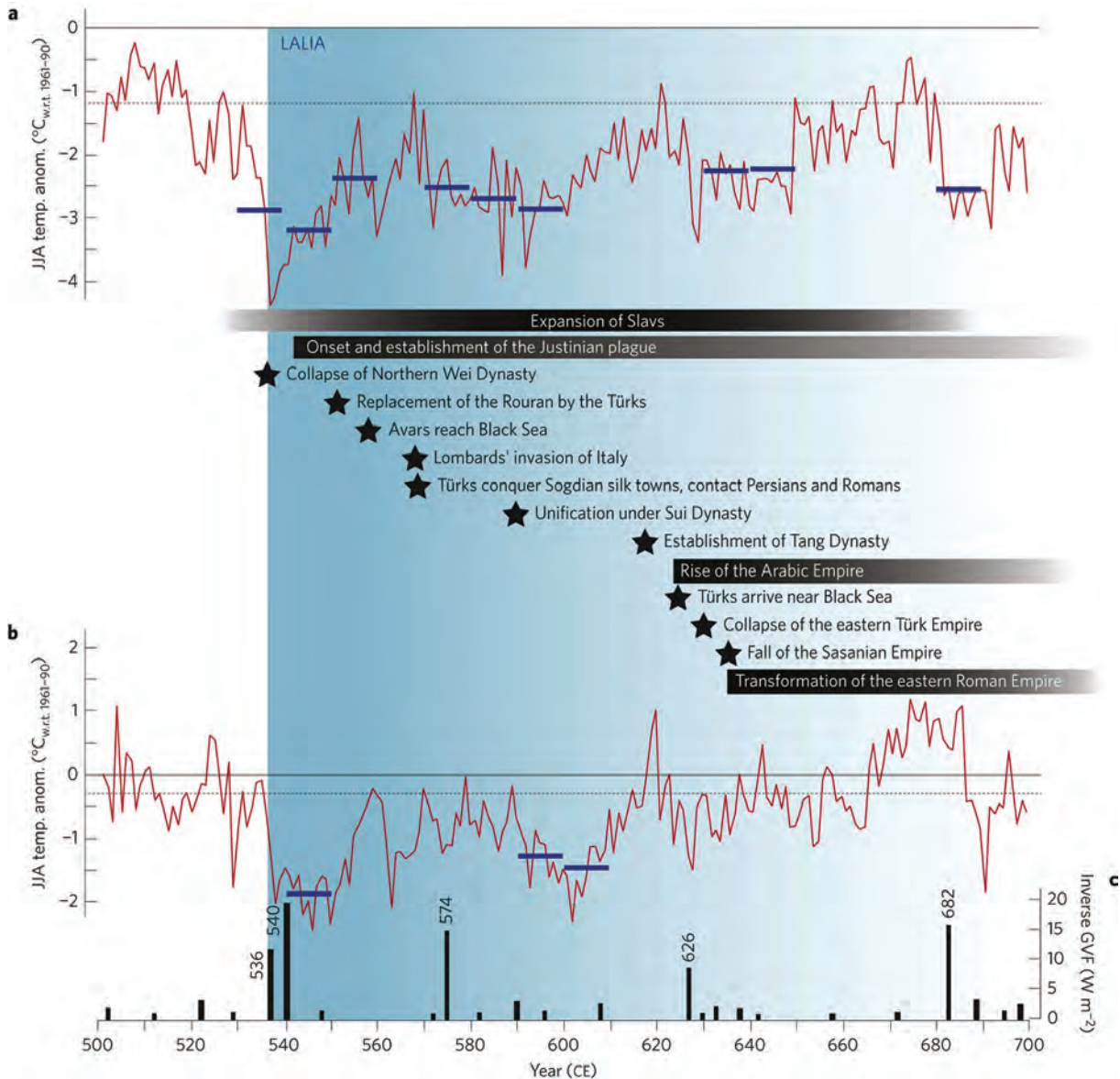

Fig. 2. Cooling and historical events during the Late Antique Little Ice Age. Reprinted from Büntgen et al. 2016. Cooling and societal change during the Late Antique Little Ice Age from 536 to around 660 AD. Nature Geoscience 9: 234, Fig. 4. https://doi.org/10.1038/ngeo2652. Reprinted with permission from Springer Nature License. For an explanation of the figure legends a-b, see O.c. 234, Fig. 4. a–c Reconstructed summer temperatures from the Russian Altai (a) and the European Alps (b), together with estimated volcanic forcing14 (c). Blue lines highlight the coldest decades of the Late Antique Little Ice Age that range among the ten coldest decades of the Common Era (AD). Horizontal bars, shadings and stars refer to major plague outbreaks, rising and falling empires, large-scale human migrations, and political turmoil. Black dashed lines refer to the long-term reconstruction mean of the Common Era (AD).

always bounded by the old systemic postulates of politics, economics, technology, and value. Bifurcations also mean points of destabilization, where even small internal and/or external triggers (climate change, political and economic aberrations, war, and migration) can produce large but gradual changes. Collapse is thus a transformational process that can take centuries, returning to less structured and less connected tribal communities. However, Renfrew also predicted that in marginal areas some of the earlier social structures would survive, triggering a process of renewed transformation into complex and centralized communities.

Joseph A. Tainter (*1988*) also defined the collapse of complex prehistoric and historical societies as a political process in which the society rapidly loses its achieved level of social and political complexity within a few decades. This leads either to its demise or to a new cycle of development. Similar to Renfrew, Tainter also assumed that this process is related to the economic effect of marginal return and how societal elites can facilitate short-term adaptation to a changing natural environment through economic strategies and intensive resource use. However, through misguided economic policies and overdeveloped social structures the elites can also trigger collapse (*Tainter 2006a*). Tainter built on James G. Miller's (*1978*) Living Systems Theory, according to which living systems are organized into interacting and interconnected subsystems, their interaction and interplay and relationship with the environment. The basic premise is that nature is a continuum of complex life organized in different patterns that are repeated at all levels of the system. However, Tainter (*2000b; Tainter, Crumley 2007*) pointed out an important difference in this context. In contrast to ecological systems, social systems develop a complexity and sustainability that are connected to the environment through an interface, *e.g.,* the process of problem solving. Thus, sustainability depends not only on the stability of the ecological system, but primarily on successful problem-solving processes. Sustainability is not the passive maintenance of equilibrium (*i.e.* stasis) in the sense of fewer and fewer people using fewer and fewer natural resources, but the achievement of rapid development and continuous functioning of the systems, organizations, and technologies needed to solve problems. This, of course, leads to increased complexity and an increased expenditure of labour, time, money and energy.

For Tainter complexity is therefore an economic function and a fundamental problem-solving tool. Complexity in human social systems correlates to *"structure and behavior, and/or degree of organization or constraint",* and the *"variety of mechanisms for organizing these into a coherent, functioning whole"* (*Tainter 1988.23; 2006b.92*). He defined sustainability as *"maintaining or fostering the development of the systemic contexts that produce the goods, services, and amenities that people need or value, at an acceptable cost, for as long as they are needed or valued"* (*Allen, Tainter, Hoeckstra 2003.26*). According to the economic principles of diminishing returns and marginal utility introduced by the neoclassical school of economics, such problem solving can only be successful within a certain period. Gradually, the point is reached where further investment in complexity no longer yields an adequate return, and higher input leads to lower output. When marginal utility is reached, each further investment in complexity contributes less to the total return than the previous investment. After an extended period of diminishing returns, problem solving becomes ineffective, sustainability becomes unstable, and societies become vulnerable. Problem-solving trajectories can span decades, generations, or centuries. They can lead to three outcomes: collapse, adaptation and recovery at a lower level of complexity, or maintenance of sustainability by increasing the level of complexity and using alternative resources. Sustainable development, then, is the ability of a society to maintain the continued functioning of its political and social structures, its hierarchy, and its continued access to economic resources (*Tainter 2006b.92; 2014.202*). As examples, he cites the collapse of the Akkadian Empire, the Eastern Roman Empire, and the Maya civilization on the one hand, and the resurgence of the Byzantine Empire and colonial Europe on the other.

An interpretative approximation to sustainability is resilience, or the ability of a system to adjust its configuration. Timothy F. H. Allen, Joseph A. Tainter, and Thomas W. Hoekstra (*2003.26*) caution against distinguishing between these two terms, as sustainability involves the ability to maintain the continuity of social systems and the conditions under which they function, whereas resilience is the ability to reconfigure social systems and adapt them to function under new circumstances. Resilience, then, is the abandonment of the principles of sustainable functioning. In contrast, Fikret Berkes *et al.* (*2003.2,6*) erase the distinction by defining sustainability as a dynamic

process and the ability of societies to adapt to climate and environmental changes. At the same time, they understand sustainability as "*maintaining the capacity of ecological systems to support social and economic systems*". They link resilience to the ability to adapt to changes within cycles of growth and renewal.

We have mentioned elsewhere (*Budja 2015*) that Crawford S. Holling introduced the concept of resilience to ecology in the early 1980s. Later it was associated with the adaptive cycle and the hierarchy of ecological and social systems (*Holling 1986*). He called it panarchy**1** and embedded it in the context of adaptive change theory (*Holling, Gunderson, Ludwig 2002.21–22*). For Holling and Lance H. Gunderson, panarchy is "*a representation of a hierarchy as a nested set of adaptive cycles. The functioning of these cycles and the communication between them determines the sustainability of a system*" (*Holling 2001.396; Gunderson, Holling 2002; Gunderson et al. 2002.14–16*). In other words, we are talking about a hierarchical structure in which natural and social systems are interconnected in a continuum of adaptive cycles of growth, accumulation, restructuring, and renewal that does not have a "*rigid, predetermined path and trajectory*" at the level of households, villages, or regions (*Holling, Gunderson 2002.51*; see also *Gunderson* et al. *1995; Folke* et al. *1998*).

Panarchy in this context objectifies a cycle with four phases of processes and events (Fig. 3). The first, the r-Phase, is characterized by exploitation, rapid migration to uninhabited or sparsely populated areas, rapid population growth, new technologies, and survival strategies. The second, the K-Phase, is characterized by a period of conservation or stagnation, mismanagement, and increasing rigidity. The third, the Ω-Phase is a period of release or creative destruction and chaotic problem solving, economic disincentives, collapse, and resettlement. The fourth and final phase, the α-Phase, is a period of reorganization and renewal (*Gunderson, Holling 2002; Berkes* et al. *2003; Walker, Salt 2006.163; Folke 2006; Scheffer 2009; Aimers, Iannone 2014*). It should be noted that due

to sudden, unpredictable, and prolonged events and processes that occur outside of these cycles, especially in the adjustment phase, complete collapse and permanent disruption of the system continuum is possible. Holling (*2001.399*) associates this with extended and cataclysmic events.

Panarchy is thus a model for the transformation of hierarchical structures into dynamic adaptive units that respond to even small perturbations in the transition from the growth phase to the Ω-Phase of collapse and transformation, and in the transition to the α-Phase of rapid growth. Cross-scale dynamics and interactions are emphasized, where revolt is followed by creative destruction and leads to a memory process. This leads to transformation and renewal. Memory preserves both history and experience about how the system works, providing "*context and sources for renewal, recombination, innovation, novelty, and self-organization following disturbance*" (*Folke 2006.259*). In other words, social (collective) long-term memory preserves information about under-
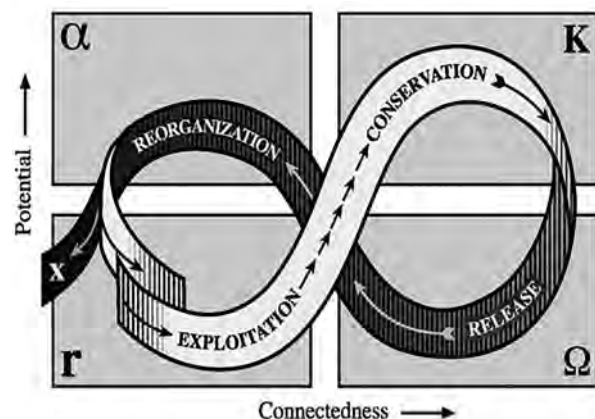

*Fig. 3. Holling's continuum of adaptive cycles (*Holling 2001.394, Fig. 4*). Four ecosystem and economic functions (r, K, Ω, α) and the cycle of events are shown. The Y-axis denotes the potential for resource accumulation and the X-axis denotes the degree of linkage between the variables. The x marks the exit from the cycle and indicates the transition to a less productive and less organized system. Short, closely spaced arrows indicate a slowly changing situation; a long dotted arrow indicates a rapidly changing situation.*

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1 The term Panarchy was coined from the words 'pan' and 'hierarchy', illustrating the correlation between change and permanence, the predictable and the unpredictable. Gunderson and Holling (*2002.5*) bring together the name of the Greek god Pan, representing change and unpredictability, and the word hierarchy, signifying structures that maintain system integrity and allow for adaptive evolution. It is worth pointing out that the term panarchy has been used in philosophy since as early as 1591. It was introduced by Franciscus Patricius in his work *Nova de universis philosophia*, which comprises four parts: *Panaugia*, *Panarchia*, *Pampsychia*, and *Pancosmia*. As part of the systems theory, it stands in contrast to hierarchy. See also Sundstrom and Allen (*2019*).

standing the dynamics of past environmental change and also about experiences related to rapid climate change and subsequent adaptations (*McIntosh* et al. *2000.24*). Panarchy is simultaneously creative and conservative, striking a dynamic balance between rapid changes and traditions on the one hand, and disturbances and interactive cross-scale dynamics on the other. The system simultaneously conserves and evolves (*Holling 2001*). Resilience thus means the ability to continually reformulate existing social structures, hierarchies, and economic practices and to restart the cycle again and again – that is, to preserve the capacity for sustainable development (*Smit, Wandel 2006; Nicoll, Zerboni 2020*; for an overview and critique of these concepts see *Soens 2020*).

John Haldon and Arlene Rosen (*2018*) developed a new approach to Formal Resilience Theory (*i.e.* Theory of Adaptive Change) using examples from late antiquity and the early Middle Ages. The basis of the theory remains the adaptive cycle in which the Social-Ecological System functions in several stages that range from "*increasing complexity, interconnectedness, and conservatism (growth or r-phase)*" to the stage where "*networks are over-connected (stability, K-Phase), limiting the system's ability to respond effectively to exogenous or endogenous stress points of stress*". This is followed by the Ω-Phase (catastrophic shift), a release that "*opens the system to many possible responses, new and/or traditional*". The Ω-Phase quickly transitions to the α-Phase, which is "*highly resilient and loosely structured, resulting in reorganization of the system and leaning to a new equilibrium with different key characteristics from those that previously dominant*" (*Haldon, Rosen 2018.277*). Catastrophic system-wide change occurs only when most of the various cycles of adaptation fail.

Historical geography and palaeoecology have also placed collapse into historical trajectories of vulnerability and environment-culture interaction scenarios. These maintain the supposition that the collapse of past civilizations is the direct consequence of climate change, referring to different economic development and demographic models based on the evolutionary paradigm of the gradual, continual and unilinear development of past societies. At the beginning of the vulnerability trajectory, they embedded the extremely vulnerable Mesolithic hunter-gatherers and Neolithic farmers, followed by less vulnerable complex and centralized and then highly productive

agrarian-urban societies. However, the latter become vulnerable again in overpopulated regions and when resource areas are overexploited. In the former, the collapse of the entire cultural-demographic system is the only response to climatic events. It is in the latter that the development of adaptive practices appeared, the beginning of which is associated with the onset of the agricultural revolution at the end of the 18th century (*Messerli* et al. *2000*).

In the context of environment-culture interactions, Paul Coombes and Keith Barber (*2005*) present four different responses of past societies to climate and environmental change. The first is the collapse of settlements and abandonment of marginal lands due to subsistence degradation, causing local populations to fall below minimum sustainable levels. In the second, there is a partial decline of settlements in marginal areas because the subsistence base deteriorates, so that the local population remains above the maximum sustainable level. In the third scenario, environmental changes lead to a sudden change in modes of agricultural production, accompanied by advances in technological and socioeconomic complexity. The scenario is based on the model of Ester Boserup (*1965; 1988*) in which demographic growth and limited economic resources (intensive use and/or loss of subsistence resources due to climatic anomalies) forced past societies to innovate and reform their production methods. The fourth response predicts the general collapse of social structures in both core and peripheral regions. It is based on the cascading failure of past complex social systems, using the key concepts of fractals and self-organized criticality from theoretical physics. It involves a simple, repeating pattern of critical events in the natural environment, politics, economics, and social relations (*Brunk 2002*). Any of these events can cause the gradual decline of a social system. For this reason, Coombes and Barber (*2005.309*) believe that the general collapse of a self-organizing system can be caused by any critical event, but they agree that the collapse of the Mesopotamian and Central American civilizations was the result of rapid climate change and associated global cooling and drought.

There has been much discussion about the definitions and relationships among the concepts of vulnerability, adaptation, and resilience, and it has been pointed out that the third has often been defined ambiguously or flexibly and cannot be related to the former two (*Brand, Jax 2007; Haldon, Rosen 2018*). The interpretative context for all three remains dominated by

collapse and disaster (*Gallopín 2006; Endfield 2012; 2014; Van Bavel* et al. *2020.2–42*).

Recent attempts to apply panarchy and adaptive cycles in archaeology have appeared in three publications. The first, *Resilience and the Cultural Landscape* (*Plieninger, Bieling 2012*), is a compilation of studies on cultural landscapes shaped by human-nature interaction. The second, *Adaptive Cycles in Archaeology* (*Bradtmöller, Riel-Salvatore, Grimm 2017*), focuses on prehistoric archaeology, which "*provides a wide spectrum of examples from which we can learn about sustainable and resilient behaviours of given groups as well as about the successful transformations of human systems that managed to maintain their integrity in the face of challenging ecological fluctuations and social turning points*" (*Grimm, Riel-Salvatore, Bradtmöller 2017.1*). The editors warn of the problems in correlating cultural and climate sequences on the one hand, and the definition of complexity on the other. Also problematic is the application of two of Holling's (*2001*) key parameters that allow the system to change in adaptive cycles, namely internal connectedness and potential. In archaeological interpretations, these are transformed into complexity within prehistoric mental and socio-ecological systems. A later work proposed replacing the two parameters with complexity proxies: subsistence, demographic trends, social organization, and technological development/innovation (*Bradtmöller, Grimm, Riel-Salvatore 2017.5–7*). The third publication, *Archaeology, Climate, and Global Change*, a special issue of the *Proceedings of the National Academy of Sciences of the United States of America* (117/15, 2020; http://onlinedigeditions.com/publication/?m=25371&i=657377&p=1&ver=html5), contains five articles on adaptation strategies related to climate change in the past on a global level. The role of archaeology is discussed in the context of interdisciplinary studies of past, present, and future climate changes and related ecological challenges (*Rick, Sandweiss 2020*). Finally, it is worth noting a number of articles that use millennia of prehistoric and historic regional cultural trajectories and climate dynamics to critically consider the validity and usefulness of Formal Resilience Theory and provide a new approach to the concept of adaptive cycles (*Allcock 2017; Haldon, Rosen 2018; Izdebski, Mordechai, White 2018; Xoplaki* et al. *2018*).

We have to mention resilience and the associated adaptive cycle in the context of human ecodynamics, *i.e.* the study of long-term change in socioecological systems. The study includes a human behavioural ecology and a cultural niche construction (*Fitzhugh* et al. *2019*). Human ecodynamics is defined as "*an umbrella term to describe humans and their environments as made up of landscapes and seascapes, and it involves collaboration between archaeologists … and researchers from other human, social, and natural sciences*" (*Holm 2016.307*). It is not an interpretive model, although the authors and the editors of *Human Ecodynamics in the North Atlantic: A Collaborative Model of Humans and Nature through Space and Time* (*Harrison, Maher 2014.3–4*) ambitiously assign it the role of a new paradigm that, through an interdisciplinary research approach, enables us to understand past human-environment interactions and formulate predictions about how humans will respond to climate change, which could lead to various forms of adaptation and growth, but also to collapse. However, the approach can be characterized as an interdisciplinary study of the coevolution of natural and socioeconomic systems in different environments over time, with archaeology playing the central role in understanding the relationships between people and their environment and in identifying problems related to the sustainable development of modern societies (*Van der Leeuw, Redman 2002*; *Degroot* et al. *2021*). Most important in this context is the collection, comparison, and correlation of palaeoclimate proxy data from archaeological records on local and regional levels (*Kirch 2005; Fitzhugh* et al. *2019.1085–1086; Sandweiss 2017*).

It is also worth mentioning the attempt to define an archaeological event in the context of past climate changes and its importance in predicting an uncertain future. Relying on the Badiou's, Žižek's, and Deleuze's philosophical conceptual reflections and seven interpretive postulates, Lull *et al.* (*2015.30*) labelled the event as a concept that should be avoided in archaeology and, in particular, should not be included in the prediction of future events because "*it is not necessary to forecast an uncertain future, since the future of past events is also past to us*".

Finally, let us present the definitions of resilience and adaptation given by the IPCC, which should be generally accepted in interdisciplinary research. Here, resilience is defined as "*[t]he capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure while also*

maintaining the capacity for adaptation, learning and transformation", and adaptation is the human "process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities" (Matthews 2018.1812). Interestingly, similar definitions of resilience as a community's ability to withstand and recover from stresses, and the postulate that the resilience of societies and their ecosystems plays a key role in ensuring our continued development in the future, appeared decades ago in an archaeological study of Aegean prehistory (*Weiberg 2012.150*). The concepts of panarchy, adaptive cycles, and resilience are presented in this study as a substitutes for systems theory, and as a conceptual tool to bridge the gap between processual and post-processual archaeology.

Rapid climate changes, prehistoric cultures and the collapses or adaptations

Little thought has been given to equating the adaptive cycle with the cultural cycle and introducing the latter into archaeology. Andreas Zimmermann (*2012*) introduced the cultural cycle as a proxy for external factors (climate change) associated with the mobility of agrarian, pre-state societies. He placed it in the context of cultural evolution and linked it to the concepts of developmental stages, cultural transformations, and Childe's (*1936*) revolutionary trajectory of civilization, known as the Neolithic-Urban-Industrial Revolutions. For central Europe, therefore, cultural cycles and epochs are assumed to overlap with a four-stage demographic model with the population growth from 1 person per 100km^2 in Mesolithic hunter-gatherer societies to 0.6 to 1.8 persons per 1km^2 in the Neolithic, Bronze Age, and Iron Age to 24 to 25 in the Roman period, after the Migration Period and before the Industrial Revolution, and to 50 persons after the Industrial Revolution (*Zimmermann 2012.251, Fig. 1*; see also *Widlok* et al. *2012*). The Neolithic Pfyn and the Linear Pottery cultures contributed a few years later to the description of the cultural cycle as a succession of four panarchic phases. Demographic trends, which can be deduced from the number of coexisting settlements, houses and wooden palisades, served as a variable to delimit and confine the phases. They were correlated with rapid climate fluctuations, *i.e.* the IRD 5b event (*Gronenborn 2012; Gronenborn* et al. *2014*) that is well documented in palaeoclimate archives but considered insignificant (*Peters, Zimmermann 2017*).

Of particular interest is on the other hand the relationship between the culture cycle and the theory of gene-culture coevolution and dual inheritance transmission (*Cavalli-Sforza, Feldman 1981; Boyd, Richerson 1985*), which is based on Darwin's concept of evolution and contrasts with Binford's (*Binford 1972. 431*) concept of culture as an extrasomatic adaptation to the environment, and thus also with Spencer's concept of evolution (*Budja in preparation*).

In prehistoric archaeology and palaeoclimatology, more attention has been paid to the correlative processes of Neolithisation and the sudden cooling events 9.2 ka and 8.2 ka, and the related palaeoclimatic archives in the eastern Mediterranean, western Asia Minor, southern Balkan Peninsula and Apennine Peninsula (*Magny* et al. *2003; 2013; Rohling, Pälike 2005*; *Rohling* et al. *2009*; *Pross* et al. *2009; Dormoy* et al. *2009; Peyron* et al. *2011; Tubi, Dayan 2013; Magny, Combourieu-Nebout 2013; Francke* et al. *2013; Siani* et al. *2013*). The 8.2 ka event is radiocarbon dated in the Greenland ice core between 8300 +10/−40 and 8140 +50/−10 BP (*Rasmussen* et al. *2014*). In explaining the correlation between the 8.2 ka climate event and the appearance of the Neolithic in Asia Minor and Europe, two scenarios have been proposed. The first assumes that rapid cooling cycles and droughts caused cultural, economic, and demographic collapse, the abandonment of settlements in the Levant, southwestern Anatolia (Catalhüyük), and Cyprus, and the migration of Neolithic farmers to southeastern Europe (*Clare* et al. *2008; Weninger* et al. *2009; 2014; Özdoğan 2014*; see also *Budja 2007*). In the second, settlement abandonment and interruption do not occur as frequently, and are documented in only a few Neolithic settlements (four out of 83). It is assumed that Early Neolithic farmers developed new social and adaptive strategies and that there was no migration to distant areas (*Flohr* et al. *2016*). Both scenarios are based on stratified Neolithic settlements and associated radiocarbon dates, as well as on the relevant palaeoclimate archives. The first scenario includes 42 settlements and 735 radiocarbon dates (*Weninger* et al. *2014*), and the second includes 83 settlements and 3397 radiocarbon dates (*Flohr* et al. *2016*). Parallel studies focused on regional precipitation regimes during the otherwise dry and cold period of the 8.2 ka event and the presumed colonization of Europe in the Early Neolithic (*Gauthier 2016*), as well as palaeohydrological and sedimentological transformations (erosion) of settlement deposits and stratigraphic superpositions directly linked to the

process of Neolithisation in the eastern Mediterranean (*Berger* et al. *2016*).

Bond's 5.9 IRD event (*e.g.,* Gronenborn's IRD 5b event) and Mayewski's 6000–5200 cal yr BP period of rapid climate change are also associated, on the one hand, with the cultural, economic, and demographic collapse of the first agricultural communities (Early Neolithic Linear Pottery culture) in central and western Europe (*Shennan, Edinborough 2007*). On the other hand, the application of the theory of adaptation, resilience, and adaptive cycles (*Gronenborn* et al. *2014; 2017; Peters, Zimmermann 2017*) has shown that rapid climate change did not have an immediate and catastrophic effect, but was only one of several destabilizing factors. For example, periods of drought and changing precipitation regimes coincide with population declines and changing settlement patterns (smaller settlements and fewer houses). The periods with more precipitation coincide with population growth. The periods with the strongest climatic fluctuations (5140/30 and 5090/80 den BC), when droughts alternate with periods of mostly heavy rainfall and periods of unusually high temperatures (5106/05 den BC), are associated with the construction of enclosures (*i.e.* village fortifications), social unrest, and violence in the eastern regions of the Linear Pottery culture cultures. In the western regions, the wetter periods after 5098 den BC also coincide with the greatest population growth. Cultural decline and population collapse follow the end of climatic fluctuations, the IRD 5b event (*Gronenborn* et al. *2014; 2017; Peters, Zimmermann 2017*). In the southern Carpathian Basin, the event was identified as the 7.1 ka BP rapid climate change and associated with the collapse of the Starčevo culture, the migration of the Linear Pottery and Vinča cultures, and the emergence and abandonment of the tell sites (*Botić 2021*).

The most recent approach is based on the assumption that more people = more sites = more ^{14}C dates, and on the statistical correlations between population fluctuations and palaeoclimate records derived from high-resolution speleothems in Central Europe from the Late Neolithic to the beginning of the Middle Bronze Age (5500–3500 cal BP) (*Großmann* et al. *2023*). The authors suggest that they found statistical correlations between population fluctuations and climate. Warm and humid periods, which increase subsistence yields and reduce the risk of crop failure, are associated with increases in population. Colder and drier climates, on the other hand, are associated

with population declines and increased risk of crop failure, marking upheavals such as the dissolution of Late Neolithic societies and the emergence of a stratified society with great social inequality.

Bernhard Weninger *et al.* (*2009.48–49*; see also *Jung, Weninger 2015*) linked Mayewski's periods of rapid climate change in 6000–5200 and 3000–2930 BP with the collapse of Copper and Bronze Age cultures (abandonment of settlement VIIb9 at Troy) in southeastern Europe and parts of Anatolia. In Mesopotamia, the periods are associated with the absence of seasonal monsoons, droughts, and cooling cycles. The first of these periods is thought to have caused the collapse of the Uruk culture in Mesopotamia and, two centuries later, the collapse of the Jemdet Nasr culture (*Brooks 2006; 2011; 2013*). In the central Sahara, the collapse of livestock and transhumance is noticeable, and settlement patterns disintegrated, as the number of settlements found above 23° latitude decreases significantly, and they are only in oases (*Vernet, Faure 2000; di Lernia 2002; Brooks 2011; di Lernia et al. 2020*). In central China, along the Yellow River, and also in Inner Mongolia, the above anomalies have been associated with a series of rapid and severe cooling cycles, changes in the South Asian monsoon regime, and the collapse of the agriculture and livestock cultures Liangzhu, Shijiahe, Shangdong-Longshan, and Laohushan (*Zhang* et al. *2000; Wu, Liu 2004; Xiao* et al. *2004*). In contrast, the collapse of Bronze Age culture occurred in radiocarbon-dated Ireland after rapid climate change had ended, and is associated with economic and social disintegration caused by the transition to a new technology (iron metallurgy) and the formation of new economic practices and social networks (*Armit* et al. *2014*).

At the theoretical level, there have been some attempts to conceptualize an archaeology of climate change based on the premise that societies have faced more than climate and environmental change in the past, and therefore this cannot be the only explanation for their collapse. Regional environmental variability and the economic, social, and emotional responses of past societies were emphasized. These can be seen in changing subsistence strategies and the formation of sacred sites and ritual landscapes (*Van de Noort 2011a; 2011b*). In contrast, Toby Pillatt (*2012.31*) proposed moving away from climate and society. His proposed key terms are weather, landscape, and social memory. He refers to weather as "*the material condition of landscape*" and landscape as "*the mate-*

rial manifestation of the relation between humans and the environment" (*O.c. 42*). Social memory is directly related to resilience theory, which serves as a conceptual and symbolic foundation that allows for the transmission of environmental behaviours from one generation to the next. Past human actions have thus always depended on how the environment was perceived, which then became collective knowledge based on past experiences and stored in collective memory.

Finally, the modern archaeological-environmental approach recognises archaeology and cultural heritage not only as a source of information about man's

Spring 1676	Balkans: severe cold
Winter 1679/80–April 1680	Ionian Sea: continuous rainfall, litanies
	South Aegean: severe cold, snowfalls
Winter-spring 1682	West Greece: drought, lack of grain, famine
Winter 1682/83	Greece: severe cold, frost, death of animals, destruction of crops, high prices, famine
Winter 1684/85	Ionian Sea: continuous rainfall, floods, destruction of buildings, high prices
Winter 1686/87	Greece: harsh cold, freezing of lake of Ioannina for 3 months, famine
1690	Serbia, Bosnia-Herzegovina: high prices, famine
	Athens: long dry period
1691	Crete: harsh cold, drought, grain did not grow
1691–1694	Crete: bad harvest, famine, high prices olive-oil
Autumn 1695–winter 1696	Aegean Sea: drought, no harvest, church litanies
1699/1700	Greece: very cold and long-lasting snow cover, snow cover over the Cretan mountains the whole 1700; bad harvest
	Thessaly: death of animals
Winter 1708/09	Serbia: severe cold, famine, plague, death of people
1710	Former Yugoslavia: bad harvest, famine
Autumn 1710–winter 1711	Ionian Sea: warm and dry, drying up of wells Ioannina; Arta: locusts
November 1712–summer 1714	Greece: drought, bad harvest, high prices, famine
	Thessaloniki: plague
Winter 1713/14	North Greece: drought, severe cold, bad grain harvest
	Serbia: severe cold, death of people
1715	Greece: great famine
1780	West-north Greece: heavy rainfalls, flooding, destruction of buildings (mostly mud constructions), high prices
	Crete: famine, plague
Winter 1782	Greece: harsh cold, freezing of lake Karla, destruction of olive-trees, fruit trees, death of animals
	Bosnia-Herzegovina: plague, death of people
Winter 1789/90	Serbia: excessive snow cover, death of people and animals
Winter-spring 1805	North Greece: heavy rainfall, death of cattle, deficient harvest
Winter 1807/08	North-central Greece: severe cold, freezing of lake Kastoria
Winter 1828/29	Greece: severe cold, long-deep snow cover, freezing of lake Kastoria, destruction of trees, death of animals

Fig. 4. The years 1675–1715 and 1780–1830 with crop failures, famines and plagues, and weather/climate events. Italics indicate the historical events and the extreme weather/climate events that the authors associate with the strong Siberian anticyclone and the westward Arctic air flow in winter and spring in the Mediterranean region. Reprinted from Xoplaki E., Maheras P. , and Luterbacher J. 2001. *Variability of Climate in Meridional Balkans During the Periods 1675–1715 and 1780–1830 and Its Impact on Human Life. Climatic Change 48: 597, Tab. II.* https://doi.org/10.1023/A:1005616424463. *Reprinted with permission from Springer Nature License.*

environment in the past, but also as a "*guide for expanding the capacity of modern global climate responses to address the complexity of man's social environment today*" (*Rockman, Hritz 2020.8296*). In this context, archaeology is not the only discipline that Dagomar Degroot *et al.* (*2021*) embed in the interdisciplinary package of science they call the history of climate and society, it also includes geography, history, and palaeoclimatology. The authors argued that interpretations of past climate are often based on fragmented and disconnected historical records, data on past climate fluctuations (*i.e.* proxy data in palaeoclimate archives), and estimates based on different statistical models that may differ substantially with respect to different time and space scales on a global scale. This can lead to a misperception of the causal mechanisms, magnitude, timing, and evolution of past climate changes. The authors rejected catastrophic scenarios but acknowledged that climate changes have had disastrous impacts on societies in the past (see also *Degroot 2018*). Using the concept of resilience and archaeological and historical examples from the Late Antique Little Ice Age and Mediaeval Little Ice Age, the authors present five pathways (strategies) of resilience that allowed societies in different regions to survive and thrive. These are: (i) the exploitation of new opportunities, (ii) resilient energy systems, (iii) trade and empire resources, (iv) political and institutional adaptations, and (v) migration and transformation (see also *Degroot* et al. *2021. Supplementary Information, Fig. 2*). The similarities with the panarchy model are of course not coincidental, although the authors do not mention it. However, they point out that their approach is key to explaining events in the past and predicting future events.

In place of a conclusion

The historical record of rapid climate anomalies and their consequences in the Balkans and eastern Mediterranean during the Little Ice Age in the 17th, 18th, and 19th centuries, which coincided with periods of lower sunspot activity (Maunder Minimum), North Atlantic ocean circulation, altered atmospheric circulation and strong volcanic eruptions, is instructive. Eleni Xoplaki *et al.* (*2001*) presented sequences of extreme events in different regions described as harsh and long winters and long periods of hot and dry and/or cold and wet periods with floods, during which crops did not grow; fields, orchards, pastures and meadows were destroyed; and domestic animals died. Food shortages, famines, plague epidemics, population decline and even depopulation of some regions were the result (Fig. 4). On the one hand, we can see these events as a sequence that occurred several times in the past and that are usually noted in archaeological records as interruptions in ^{14}C sequences and population and cultural trends. On the other hand, it allows us to verify the theoretical concepts of panarchy, and the cycles of adaptation and resilience that are thought to have been developed by pre-industrial societies.

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