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LETTER

Potential responses and resilience of Late Chalcolithic and Early Bronze Age societies to mid-to Late Holocene climate change on the southern Iberian Peninsula

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27 April 2021Mara Weinelt^{1,*}, Jutta Kneisel¹, Julien Schirrmacher¹, Martin Hinz^{1,2}  and Artur Ribeiro¹¹ Institute of Prehistoric and Protohistoric, Kiel University, Kiel, Germany² Institute for Archaeological Sciences IAS, Dept. of Prehistoric Archaeology, University of Bern, Bern, Switzerland

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E-mail: Mweinelt@roots.uni-kiel.de**Keywords:** mid Holocene climate change, western Mediterranean, Bronze Age, Chalcolithic, resilienceOriginal content from
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citation and DOI.**Abstract**

In this investigation, we use a socio-environmental multi-proxy approach to empirically test hypotheses of recurrent resilience cycles and the role of climate forcing in shaping such cycles on the Iberian Peninsula during mid-Holocene times. Our approach combines time series reconstructions of societal and environmental variables from the southern Iberian Peninsula across a 3000 yr time interval (6000–3000 cal yr BP), covering major societal and climate reorganisation. Our approach is based on regional compilations of climate variables from diverse terrestrial archives and integrates new marine climate records from the Western Mediterranean. Archaeological variables include changes in material culture, settlement reconstructions and estimates of human activities. In particular, both detailed chronologies of human activities evolving from the Late Neolithic to the Bronze Age and mid- to Late Holocene climate change across the mid-Holocene are compared, aiming to assess potential human responses and coping processes associated with abrupt mid-Holocene climate changes.

1. Introduction

Climate change is regarded as one of today's major challenges threatening the stability of human communities. It is particularly ranked among the main causes of large-scale population movement and international migration. Predictions of the IPCC 2019 report estimate up to 200 million people who will be displaced by shoreline erosion, coastal flooding and agricultural disruption by 2050 (IPCC 2019). Implications for societies and environments (feedbacks and amplification) are therefore increasingly discussed with hypotheses of climate impact on social stability, social resilience, environmental vulnerability and economic wealth. A coupling of social and ecological resilience is often postulated (e.g. Adger 2000), based on definitions of social resilience as the ability of groups or communities to cope with external stresses and disturbances resulting from social, political and environmental change. Accordingly, environmental variability can increase the risk of being dependent on particular resources through the incidence of extreme

events in nature, such as drought or flood, or from the impact of pests and diseases on agricultural systems. A long-term perspective as provided by concerted palaeoecological and archaeological reconstructions extending over a period of several millennia can help to better understand such independencies (e.g. Finné *et al* 2011, 2019, Izdebski *et al* 2016, Bevan *et al* 2017).

The western Mediterranean area and the Iberian Peninsula, in particular, are hot spots of ongoing and predicted climate change. Proneness to desertification with predictions for temperature increase and precipitation decrease above global averages are reckoned hazardous for social and environmental stability alike. Exposure to severe climate changes, marking the interfaces of subtropical and temperate climate domains under variable influence of Mediterranean and Atlantic climate constraints, has been a challenge for western Mediterranean populations throughout the Holocene. These challenges must have demanded highly adaptive and transformational processes. Arguably, these challenges were amplified during mid-Holocene times under

the constraints of major climate reorganisation and interfering responses of increasingly complex and rapidly expanding societies (e.g. Chapman 1990, Carrión *et al* 2007, Lull *et al* 2015).

1.1. Mid-Holocene climate constraints in the western Mediterranean area

A growing body of new climate records and model approaches, including an array of recent climate syntheses for the western Mediterranean area, have contributed to a more coherent picture of Holocene climate dynamics and its environmental implications. This is particularly true for the Common Era for which detailed climate and environmental reconstructions of marine and terrestrial climate variables have revealed complex patterns with interfering and closely coupled effects of high and low latitude climate forcing, including a major role of the North Atlantic sea surface temperature (SST) field (Abrantes *et al* 2017). The preceding mid-Holocene timeframe was marked by a long-term trend of insolation decrease and also punctuated by events of rapid climate change (Wanner *et al* 2011). Yet the patterns and forcing of mid-Holocene climate variability in the western Mediterranean area are not entirely understood, thus hampering direct comparisons of societal and climate variables on a supra-regional scale (Bini *et al* 2019). Recent compilations, integrating a variety of terrestrial and new marine climate archives, contribute to a more coherent picture of temperature and precipitation patterns in the Western Mediterranean (Bini *et al* 2019, Schirrmacher *et al* 2020). They highlight the severe manifestations of rapid climate change in this marginal region and the hazards related to precipitation failure, in particular. Detailed reconstructions of hydroclimate changes inferred from a stalagmite record of the El Refugio cave in Southeast Iberia imply a southward displacement of the North Atlantic Subtropical High transgressively, influencing Iberian climates over the course of the mid-Holocene (Walczak *et al* 2015). This record pinpoints the onset of Mediterranean climates at 5300 cal yr BP that went along with enhanced seasonality when precipitation is mainly received during winter. Based on a marine record near the Azores Islands, Repschläger *et al* (2017) have similarly reconstructed a southward shift of the Azores Front marking the northern rim of the North Atlantic subtropical gyre. Yet, this transition is registered here only around 4200 cal yr BP (Weinelt *et al* 2015). Iberian vegetation reconstructions spanning that time generally indicate a decrease in arboreal pollen and an increase of species influenced by changes in both climate and human impact (e.g. Carrión *et al* 2007, Schneider *et al* 2016). These records are, however, controversially interpreted in terms of either enhanced human land use intensity or as vegetation responses to dryer and cooler conditions (e.g. Schneider *et al* 2016, Schirrmacher *et al* 2019). Marine records suggest a tight link between North

Atlantic circulation patterns and the inflow of surface waters into the Mediterranean that played a major role in controlling mid-Holocene climatic variability of this region (Català *et al* 2019, Jalali *et al* 2019, Schirrmacher *et al* 2019). Based on a detailed $\delta^{18}\text{O}$ record from Lake Sidi Ali (Middle Atlas, Morocco), Zielhofer *et al* (2019) postulate, in contrast, a decoupling of subtropical and North Atlantic climate constraints. Perçoiu *et al* (2019) hypothesised that atmospheric blocking induced by a strengthened Siberian High led to drying in West Asia with implications for the western Mediterranean area. Schirrmacher *et al* (2020) traced the spatial manifestations of the 4.2 kyr BP event in a sequence of 200 yr time slices based on an extensive survey across Iberian climate and environmental records, integrating marine records as well as a broad range of different proxies from different climate archives. They found a culmination of dry and cool conditions around 4000–3800 cal yr BP, which affected the southeastern Peninsula, in particular. Carrión *et al* (2007) have shown that the impact of increasingly drier conditions on southern Iberian vegetation was reinforced by enhanced human interventions from 4000 cal yr BP onwards, as monitored in particular by enhanced grazing as well as by the repeated appearance of fires. Much attention is being focused on this arguably global 4.2 kyr BP climate event, roughly marking the mid- to Late Holocene transition, and in the western Mediterranean area marking the onset of the Mediterranean climate. Given its coincidence with the transition from the Chalcolithic to the Bronze Age in that region, it provides an excellent archive to explore human responses, coping strategies and adaptive potentials to deal with adverse climate challenges in the past.

1.2. Resilience hypotheses and mid-Holocene socio-environmental dynamics

In social sciences, for the exploration of the resilience of modern societies some diagnostic elements of resilience variability at the community level are observed through proxies, such as formal sector employment, recorded crime rates, and demographic factors (e.g. Machlis *et al* 1997). While these indicators enable the examination of links to changes in the production of the resources on which communities are 'dependent', such diagnostic proxies are generally not accessible for ancient societies. Instead, archaeological studies tackling with the reconstruction of pertinent variables over longer past time spans have to rely on remains of material culture, which reflect, for example, ideological changes and economic practices. Such variables are generally not continuously recorded over longer time intervals. In archaeological theory, resilience is often viewed using conceptual models of adaptive cycles, where a tipping point is preceded by a phase of increasing diversity/complexity and followed by a collapse of diversity/complexity (e.g. Gronenborn *et al*

2017). According to archaeological resilience theory, a single adaptive cycle evolves in four behavioural phases, namely growth/exploitation, conservation, release, and reorganisation, with each domain exhibiting a different value of resilience and degree of connectedness (Bradtmöller *et al* 2017). Such concepts have been exemplified with a variety of archaeological scenarios, generally using changes in material culture as proxies to assess changes in societal complexity. In a resilience study based on a high-resolution data set of Early Neolithic ceramic style and demographic changes and an obvious coincidence of a change in social diversity (as inferred from ceramic style patterns) with a climate event, Gronenborn *et al* (2017) concluded that climate may well have played a role in shaping this particular social trajectory. In their case study, socio-cultural variables preceded demographic changes by several generations. Yet a number of recent archaeological studies claim that climate does not play a major role in shaping such patterns. They rather invoke internal socio-political decision patterns to fully explain changes in past resilience dynamics and prehistorical boom and bust cycles (e.g. Shennan *et al* 2013, Armit *et al* 2014, Hofmann *et al* 2019). In contrast, Turchin and Nefedov (2009), who explored population dynamics of secular scale across premodern and back to Roman societies in England, France, and Russia, state that climate may become a significant factor under higher population pressure. For the Iberian Peninsula, modelled population patterns suggest that population changes of prehistoric hunter-gatherers were intimately linked to profound environmental changes (Fernández-lópez de Pablo *et al* 2019). A rapid postglacial population decrease, for instance, was related to the cold reversal of the Younger Dryas. An array of studies have explored the emergence of complex agrarian and socio-economic systems for Iberian Chalcolithic (García Sanjuán and Murillo-Barosso 2013, Valera 2015) and Early Bronze Age societies (Lull *et al* 2015), highlighting sophisticated and highly efficient strategies of resource management. Yet little reference is made by these studies to the impacts of climate change on these complex systems, and potential responses to environmental stress. Parcero-Oubiña *et al* (2019) explored the relevance of the notions of social resistance and resilience at the transition from the Bronze Age to the Iron Age on the northwestern Iberian Peninsula and found no general patterns of social division and inequality to have fostered resilience prior to the Late Iron Age.

Today, it is widely accepted that the 4.2 kyr BP event, rather than a mere climate event, was a socio-environmental event with complex interactions and feedbacks of socio-economic and socio-environmental processes (e.g. Weiss *et al* 1993, Weiss 2016). A pivotal role of climate along this socio-environmental ‘marker’, namely a long-lasting drought (i.e. spanning several decades, see Weiss 2015), is well-documented in the Eastern

Mediterranean and Near East to have triggered major migration waves. Here, demographic pressure resulting in enhanced mobility led to the collapse of urban centres and intensified conflicts. The roughly contemporaneous ‘collapse’ of Chalcolithic life-styles on the western Iberian Peninsula, as paralleled by a phase of considerable climate variability, has therefore likewise been tentatively attributed to this event of arguably hemispheric or even global extent and different regional manifestation (e.g. Bini *et al* 2019). The divergent trajectories of societies across the southwestern and southeastern Iberian Peninsula, however, open questions if this might be explained by different resilience levels or rather by differential exposure to environmental stress.

Poor empirical underpinning exists so far for the sequential behaviour of complex socio-environmental systems potentially shaping recurrent resilience patterns. Little is known about the occurrence, duration and timing of such resilience cycles. The response times of social change with regard to climate and environmental disturbances, the recurrence of such patterns in the long run, and its potential acceleration across the Holocene under increasing population pressure and variable climate constraints remain widely open questions. Siegmund (2013) systematically explored the absolute duration of individual archaeological phases in archaeological chronology systems and found highly variable durations across archaeological epochs, ranging from decades to centennials, irregularly distributed in space and time. The centennial scale dynamics in historical agrarian societies and causal connections between demographic, economic, and political variables have been explored by Turchin and Nefedov (2009). By examining an array of 32 archaeological scenarios across the globe, Peregrine (2018) found evidence for bi-modal resilience behaviour, depending on the extent of the effects of a climate/environmental event. Weiberg and Finné (2018) explored resilience patterns of the ancient Late Bronze Age (LBA) Peloponnese under climate stress, using socio-political variables spanning a time interval of 750 yr (3750–3000 cal yr BP). Testing the hypotheses that stable climate conditions favour the formation of agrarian states, while persistently volatile climatic conditions can contribute to the episodic collapse of these complex societies they found differential evidence over time. In particular ongoing arid conditions during much of the LH II, had no lasting effect on societal expansion. The authors argue that the lower levels of societal complexity made the society of the LHII less sensitive to arid conditions.

A set of variables considered as important indicators of resilience that can be at least partially approached through archaeological reconstructions over longer time spans and wider regional areas as well as across differential cultural entities include demographic change, mobility and migration. In this

context, enhanced mobility and migration may be also seen as mitigation strategies to cope with natural hazards (e.g. Bettini 2014), contrasting the idea of ‘climate refugees’, a term suggesting vulnerability of migrants rather than resilience.

Large progress has been made in recent years to quantitatively reconstruct the intensity of prehistorical human activities across Europe (and beyond), based on land use reconstructions (e.g. Kaplan *et al* 2010, Zanon *et al* 2018, Feeser *et al* 2019), settlement intensities (e.g. Hinz *et al* 2019), and on past demographic changes (e.g. Shennan *et al* 2013). Population dynamics evolving in ‘boom and bust cycles’ have been explored by an array of investigations, including Neolithic and Bronze Age studies. Estimates of these variables are approached through a variety of quantitative or semi-quantitative proxies, ranging from local to global scales (e.g. Balsera *et al* 2015, Bevan *et al* 2017, Hinz *et al* 2019). Moreover, socio-economic variables related to inequality have been empirically explored (e.g. Kohler *et al* 2017). Such proxy approaches enable comparisons of these variables across a variety of archaeological scenarios and regions and for various cultural entities, in order to better assess regional, supra-regional and global developments. In addition, numerical modelling approaches are greatly improving our understanding of the dynamics and interactions of these variables in time and space (e.g. Lemmen and Wirtz 2014). Such efforts are also encouraged by climate studies aiming to assess the impact of human activities on climate change. Numerical climate models increasingly revert to archaeological data and estimates of population changes, in particular, in order to describe changes in land use intensity and their potential feedbacks on climate and on carbon cycle scenarios (e.g. Kaplan *et al* 2010, Harrison *et al* 2020).

An array of studies has tackled with the reconstruction of demographic developments on the Iberian Peninsula based on sum calibrated archaeological ^{14}C data, and has shown large-scale population dynamics with boom and bust cycles from the Neolithic to the Common Era (Balsera *et al* 2015, Lillios *et al* 2016, Blanco-González *et al* 2018, Hinz *et al* 2019). While the data sets (i.e. ^{14}C data from archaeological contexts) underlying these studies partially overlap, they provide robust evidence of large-scale population developments on the Iberian Peninsula. On the SW Iberian Peninsula, in particular, where the prominent and numerous ditched enclosures widely disappeared within a brief time interval, a ‘collapse’ of Chalcolithic life styles is suggested around 4200 cal yr BP. This rapid decline abruptly ended a time of extraordinarily long-lasting occupation suggesting prolonged social stability (approx. 1000 yr). Some of these sites have become key sites to explore the development of social differentiation and complexity on the Iberian Peninsula (e.g. Perdigoes, Alentejo (Valera 2015) and Valencina de la

Concepción, Andalusia (García Sanjuán *et al* 2018)). In the case of Valencina, highly dynamic and ultimately unstable social differentiation has been suggested. For both sites, a final occupation phase is already suggested to have been marked by an erosion of socio-cultural practices (Valera 2015, García Sanjuán *et al* 2018). Subsequently, low population levels, as suggested by rare and more dispersed settlement findings, only reversed centuries later in the LBA. Different developments are reported from southeast Iberia, a region where Chalcolithic lifestyles apparently experienced some continuity with the contemporaneous rise of the Bronze Age El Argar culture (e.g. Lull *et al* 2015). This was marked by a boost of human activities, the rapid establishment and spread of new cultural entities, and the development of novel social organisation concerning nearly all spheres of human activity, reflecting the establishment of profoundly new ideologies (e.g. Lull *et al* 2015). Its boom phase started around 4200 cal yr BP with maximum expansion levels prevailing during several centuries, which rather brusquely ended around 3500 cal yr BP.

The scenarios of profound social and environmental transformations under mid-Holocene climate reorganisation provide an appropriate background to explore the socio-environmental dynamics in the long term. Hypotheses are tested concerning the role of climate-induced socio-environmental stress on resilience. In this context, we compare the developments of human activities on the southwestern and southeastern Iberian Peninsula against climate change using a multi-proxy approach combining reconstructions of societal and environmental variables. Detailed time series of human activities and of climate change spanning a 3000 yr time interval, namely lasting from 6000 to 3000 cal yr BP, are explored. Our study aims to reconstruct socio-environmental variability and its potential relationship with resilience, and the potential role of climate induced migration. Questions are addressed regarding the response times of social change with regard to climate and environmental disturbances, and the recurrence of socio-environmental patterns.

1.3. Methods

To explore the variability of social and environmental changes on the southern Iberian Peninsula, we use subsets of a recent data compilation by Schirrmacher *et al* (2020), exploring the spatial patterns of climate and settlement dynamics on the Iberian Peninsula during the Chalcolithic and the Bronze Age. In particular, we use stacks of the z -scored time series of precipitation and temperature changes for the southwestern and southeastern regions respectively (figure 1), which are labelled SW/SE ensembles in the following. They cover an area south of 40°N , with SE and SW areas extending west and east of -5.5° longitude, respectively, and include marine sites from

the adjacent Mediterranean and Iberian margin areas. The ensembles span a 3000 yr time period, extending between 6000 and 3000 yr BP and corresponding to 4050–1050 yr on BCE scale, ranging from the mid-Holocene to the earlier Late Holocene/the Late Neolithic to the LBA. Only well-dated time series were retained in the data base with high-resolution, spanning the major part of the 3000 yr interval as categorised by quality flags 1 and 2 (Schirrmacher *et al* 2020). The stacked and smoothed records are considered to narrow down the uncertainties and noise of local effects, individual age models and from different proxies. Thus, the stacked data are considered to robustly record climate variability on a wider regional scale. Specifically, the SW (SE) temperature ensemble is comprised of data from six (8) individual records, the SW (SE) annual precipitation ensembles from nine (20) records, and the winter precipitation ensemble from 20 (17) individual records. Site locations, proxies underlying the individual records, and original citations are listed in table 1. To ease comparison of environmental and archaeological variables all time series are reported on BP scales (cal yr BP), accordingly the archaeological variables originally calibrated to BCE scales have been converted to BP (i.e. +1950 yr).

Time series of precipitation and temperature were assembled from proxy reconstructions originating from a range of different climate archives, including terrestrial records from lakes, speleothems, and some marine records (table 1). To enable inter-comparison of highly diverse proxy data, the individual records were *z*-scored, yielding a standardised dimensionless measure of variability. An upgraded version of Schirrmacher *et al*'s (2019), Schirrmacher *et al* (2020) data base is available through PANGAEA. Marine records include, in particular, new multiproxy records from two sites from the Gulf of Cadiz (GeoB5901-2) and from the Alboran Sea (ODP site 161-97A) (Schirrmacher *et al* 2019). They provide quantitative estimates of annual and seasonal SST (method according to Pflaumann *et al* 1996, Salgueiro *et al* 2014), and of relative precipitation changes based on *n*-alkane concentrations preserved in marine sediments (Schirrmacher *et al* 2019). These well-dated records (Schirrmacher *et al* 2020) enable quantitative estimations of the magnitude of the climate shifts, as considered relevant for climate changes at the southwestern and southeastern Iberian coastal areas. The time series enable an average temporal resolution of 30 yr (ODP site 161-97A) to 70 yr (GeoB5901-2) as required to assess multi-decadal to multi-centennial climate variability.

Reconstructions of human activities are based on sum probability densities (SPDs) calculated by sum calibrating ^{14}C data from archaeological contexts. The use of this proxy to reconstruct population fluctuations through prehistorical times is based on the simple assumptions that more people produced

more archaeological finds, and that the ^{14}C sample has been taken in a balanced way across time. SPDs are generally considered to robustly record changes in population density when applied on large data sets, ideally with random distributions of finds. Over the past decade extensive data surveys and compilations have generated an excellent data base, which is available through an array of archaeological data repositories (e.g. Radon and RadonB, hosted at the Institute of Prehistoric and Protohistoric Archaeology of Kiel University). Here we use this proxy in a broad sense as a proxy of human activities, further assuming that the intensity of human activities is positively correlated to resilience. The data base used here was originally compiled by Hinz *et al* (2019), and slightly modified by Schirrmacher *et al* (2020). The data set is comprised of 984 entries for the SW Iberian Peninsula and 1376 for the SE. It merges existing data sets from the Iberian Peninsula from various data bases as outlined by Hinz *et al* (2019). Given the sensitivity of this proxy to various biases, independent archaeological evidence is necessary to test its regional performance. Complementary archaeological information is provided on settlement activities to test the robustness of the SPD data and aoristic data based on selected material culture. Aoristic approaches are based on dividing archaeological finds according to their archaeological sub-period (here Neolithic, Early, Full and Final Chalcolithic, Early, Middle Bronze Age (EBA, MBA) and LBA into a sequence of 100 yr time spans. Differential dating accuracy assigned to each registered artifact enables to depict the abundances of finds in a chronological distribution curve (e.g. Kneisel *et al* 2019). Aoristic settlement sum probabilities are based on 1437 archaeological sites with settlement character from Southern Portugal (Hinz *et al* 2019). Aoristic sum data is based on data collections from Brandherm (2003, daggers); Schuhmacher (2012, ivory), and from Murillo-Barroso and Martín-Torres (2012, amber). While amber and ivory are proxies for exchange, daggers indicate the emergence of first weapon-usable bronze tools. Continuous archaeological evidence of socio-cultural trajectories is provided by the well-dated record of the Andalusian mega-site 'Valencina de la Concepción', a key site which represents the ideological changes and social inequality of Southern Iberia (García Sanjuán *et al* 2018). This site located at the lower Guadalquivir basin near Seville (i.e. at the eastern rim of our SW region) extended over an area of up to 450 ha and exhibits an extraordinarily long occupation time spanning a 1500 yr period from the Late Neolithic to the Middle Bronze Age. Bayesian modelling, based on an overall suite of 170 ^{14}C data of archaeological finds from that site, has enabled a 25 yr step resolution of major cultural changes, variable funerary practices, and changes of non-funerary activities, in particular (data set from García Sanjuán *et al* 2018).

Table 1. Climate records used for SW and SE ensembles of this study.

Name	Latitude	Longitude	Ensemble	Archive	Proxy	References
<i>Annual</i>						
El Maíllo	40.546667	-6.209722	SW	Terrestrial	Pollen WAPLS	Ilvonen et al in review
Navarrés	39.093333	-0.683333	SE	Terrestrial	Pollen WAPLS	Ilvonen et al in review
MD03-2699	39.036700	-10.660500	SW	Marine	<i>n</i> -alkane concentration	Palumbo et al (2013)
Villaverde	38.800000	-2.366667	SE	Terrestrial	Xerophytes	Carrión et al (2001a)
D13882	38.634500	-9.454200	SW	Marine	<i>n</i> -alkane concentration	Rodrigues et al (2009)
D13902	38.554000	-9.335500	SW	Marine	<i>n</i> -alcohol concentration	Rodrigues et al (2009)
Siles	38.400000	-2.500000	SE	Lacustrine	Xerophytes	Carrión (2002)
El Sabinar ^a	38.200000	-2.116667	SE	Terrestrial	Xerophytes	Carrión et al (2004)
Elx	38.174444	-0.752778	SE	Terrestrial	Xerophytes	Burjachs et al (1997)
Santo André ^a	38.083333	-8.783333	SW	Terrestrial	Chenopodiaceae	Santos and Sánchez Goni (2003)
Cañada de la Cruz ^a	38.066667	-2.700000	SE	Lacustrine	Xerophytes	Carrión et al (2001b)
MD95-2042	37.799833	-10.166500	SW	Marine	Chenopodiaceae	Chabaud et al (2014)
Antas	37.208333	-1.823611	SE	Terrestrial	Xerophytes	Pantalón-Cano et al (2003)
PO1-5	37.085105	-8.138509	SW	Terrestrial	Artemisia	Schneider et al (2016)
Borreguil de la Virgen	37.054167	-3.377778	SE	Lacustrine	Artemisia	Jiménez-Moreno and Anderson (2012)
Laguna Hondra	37.048000	-3.294333	SE	Lacustrine	Calcium/titanium ratio	Mesa-Fernández et al (2018)
Laguna de Río Seco	37.040500	-3.342833	SE	Lacustrine	Artemisia	Anderson et al (2011)
Padul	37.011047	-3.603906	SE	Terrestrial	Xerophytes	Ramos-Román et al (2018)
Doñana	36.941667	-6.413333	SW	Terrestrial	Amaranthaceae	Jiménez-Moreno et al (2015)
Sierra de Gádor ^a	36.900000	-2.916667	SE	Lacustrine	Xerophytes	Carrión et al (2003)
Roquetas de Mar	36.794444	-2.588889	SE	Terrestrial	Xerophytes	Pantalón-Cano et al (2003)
San Rafael	36.773611	-2.601389	SE	Terrestrial	Xerophytes	Pantalón-Cano et al (2003)
San Rafael	36.773611	-2.601389	SE	Terrestrial	Pollen WAPLS	Ilvonen et al in review
Lake Medina	36.617778	-6.053611	SW	Lacustrine	Ostracod assemblages	Schröder et al (2018)
El Refugio Cave	36.583333	-4.583333	SE	Speleothem	CT density	Walczak et al (2015)
TTR14-300G	36.358867	-1.791783	SE	Marine	Lanthanum/lutetium ratio	Cortés-Sánchez et al (2011)
ODP-161-976A ^a	36.205333	-4.312667	SE	Marine	Pollen MAT	Combourieu Nebout et al (2009)
MD95-2043	36.143333	-2.621167	SE	Marine	Pollen MAT	Bini et al (2019); Fletcher et al (2010); Peyron et al (2017)
MD95-2043	36.143333	-2.621167	SE	Marine	Xerophytes	Fletcher and Sánchez Goni (2008)

(Continued)

Table 1. (Continued.)

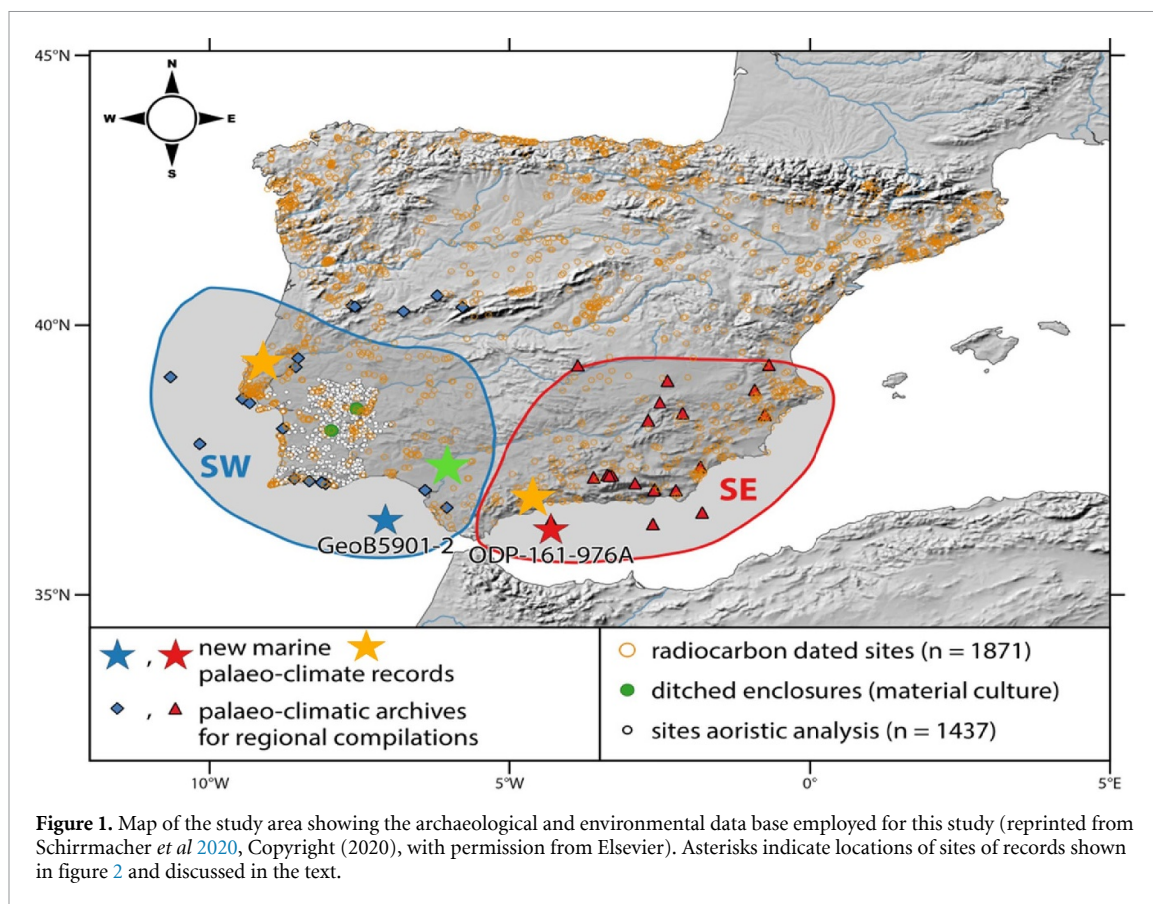
Name	Latitude	Longitude	Ensemble	Archive	Proxy	References
<i>Winter</i>						
El Maíllo	40.546667	-6.209722	SW	Terrestrial	Arboreal pollen	Morales-Molino <i>et al</i> (2013)
Lagoa Comprida	40.3622778	-7.63611	SW	Terrestrial	Arboreal pollen	van den Brink and Janssen (1985)
Charco de Candieira	40.341667	-7.576389	SW	Terrestrial	Arboreal pollen	van der Knaap and van Leeuwen (1995)
Peña Negra	40.334722	-5.792222	SW	Terrestrial	Arboreal pollen	Abel-Schaad and López-Sáez (2013)
El Payo	40.253333	-6.771111	SW	Terrestrial	Arboreal pollen	Abel Schaad <i>et al</i> (2009)
51.029	39.387519	-8.532257	SW	Terrestrial	Arboreal pollen	Vis <i>et al</i> (2010)
ALP III	39.221083	-8.568478	SW	Terrestrial	Arboreal pollen	Vis <i>et al</i> (2010)
CC-17 ^a	39.083333	-3.866667	SE	Terrestrial	Arboreal pollen	Dorado Valiño <i>et al</i> (2002)
Villaverde	38.800000	-2.366667	SE	Terrestrial	Arboreal pollen	Carrión <i>et al</i> (2001a)
Villena ^a	38.629667	-0.919889	SE	Terrestrial	Aridity ratio	Jones <i>et al</i> (2018)
Elx	38.174444	-0.752778	SE	Terrestrial	Arboreal pollen	Burjachs <i>et al</i> (1997)
Santo Andre ^a	38.083333	-8.783333	SW	Terrestrial	Arboreal pollen	Santos and Sánchez Goñi (2003)
Cañada de la Cruz ^a	38.066667	-2.700000	SE	Lacustrine	Arboreal pollen	Carrión <i>et al</i> (2001b)
MD95-2042	37.799833	-10.166500	SW	Marine	Arboreal pollen	Chabaud <i>et al</i> (2014)
Antas	37.208333	-1.823611	SE	Terrestrial	Arboreal pollen	Pantaléon-Cano <i>et al</i> (2003)
ABI 05/07	37.152416	-8.594227	SW	Terrestrial	Arboreal pollen	Schneider <i>et al</i> (2016)
ADP 01/06	37.110503	-8.345146	SW	Terrestrial	Arboreal pollen	Schneider <i>et al</i> (2016)
PO1-5	37.085105	-8.138509	SW	Terrestrial	Arboreal pollen	Schneider <i>et al</i> (2016)
VDL PP	37.055965	-8.074490	SW	Terrestrial	Arboreal pollen	Schneider <i>et al</i> (2016)
Borreguil de la Virgen	37.054167	-3.377778	SE	Lacustrine	Arboreal pollen	Jiménez-Moreno and Anderson (2012)
Laguna de Río Seco	37.040500	-3.342833	SE	Lacustrine	Arboreal pollen	Anderson <i>et al</i> (2011)
Padul	37.011047	-3.603906	SE	Terrestrial	Arboreal pollen	Ramos-Román <i>et al</i> (2018)
Doñana	36.941667	-6.413333	SW	Terrestrial	Arboreal pollen	Jiménez-Moreno <i>et al</i> (2015)
Sierra de Gádor ^a	36.900000	-2.916667	SE	Lacustrine	Arboreal pollen	Carrión <i>et al</i> (2003)
Roquetas de Mar	36.794444	-2.588889	SE	Terrestrial	Arboreal pollen	Pantaléon-Cano <i>et al</i> (2003)
San Rafael	36.773611	-2.601389	SE	Terrestrial	Arboreal pollen	Pantaléon-Cano <i>et al</i> (2003)
Cabo de Gata	36.771389	-2.228611	SE	Terrestrial	Arboreal pollen	Burjachs and Expósito (2015)
GeoB5901-2 ^a	36.380000	-7.071333	SW	Marine	<i>n</i> -alkane concentration	Schirrmaier <i>et al</i> (2019)
ODP-161-976A ^a	36.205333	-4.312667	SE	Marine	<i>n</i> -alkane concentration	Schirrmaier <i>et al</i> (2019)
ODP-161-976A ^a	36.205333	-4.312667	SE	Marine	Pollen MAT	Combourieu Nebout <i>et al</i> (2009)
MD95-2043	36.143333	-2.621167	SE	Marine	Pollen MAT	Bini <i>et al</i> (2019; Fletcher <i>et al</i> 2010; Peyron <i>et al</i> 2017)
MD95-2043	36.143333	-2.621167	SE	Marine	Arboreal pollen	Fletcher and Sánchez Goñi (2008)

(Continued)

Table 1. (Continued.)

Name	Latitude	Longitude	Ensemble	Archive	Proxy	References
Temperature						
<i>Annual</i>						
MD03-2699	39.036700	-10.660500	SW	Marine	Alkenones	Rodrigues <i>et al</i> (2010)
D13882	38.634500	-9.454200	SW	Marine	Alkenones	Rodrigues <i>et al</i> (2009)
D13902	38.554000	-9.335500	SW	Marine	Alkenones	Rodrigues <i>et al</i> (2009)
MD01-2444	37.561333	-10.142167	SW	Marine	Alkenones	Martrat <i>et al</i> (2007)
GeoB5901-2 ^a	36.380000	-7.071333	SW	Marine	Alkenones	Schirrmacher <i>et al</i> (2019)
M39008-3	36.380000	-7.071667	SW	Marine	Alkenones	Cacho <i>et al</i> (2001)
HER_GC_T1	36.370146	-4.299015	SE	Marine	Alkenones	Ausin <i>et al</i> (2015)
ODP-161-976A ^a	36.205333	-4.312667	SE	Marine	Alkenones	Schirrmacher <i>et al</i> (2019)
ODP-161-976A ^a	36.205333	-4.312667	SE	Marine	Pollen MAT	Combourieu Nebout <i>et al</i> (2009)
TTR-17_434G	36.205220	-4.312250	SE	Marine	Alkenones	Rodrigo-Gámiz <i>et al</i> (2014)
TTR-12_293G	36.173567	-2.754667	SE	Marine	Alkenones	Rodrigo-Gámiz <i>et al</i> (2014)
TTR-12_293G	36.173567	-2.754667	SE	Marine	TEX86	Kim <i>et al</i> (2015)
MD95-2043	36.143333	-2.621167	SE	Marine	Alkenones	Cacho <i>et al</i> (1999)
ODP-161-977	36.031700	-1.955283	SE	Marine	Alkenones	Martrat <i>et al</i> (2007)

^a Age model revised by Schirrmacher *et al* (2020).



In order to explore the recurrence of potential cycles and to identify periodicities inherent to records of climate and archaeological variables, time series analyses were performed using Lomb periodograms for unevenly sampled records and employing automatic detrending as provided in the palaeontological statistics software package PAST4.03 (Hammer *et al* 2001). The stacked ensembles of *z*-scored precipitation and temperature records, and the speleothem records, in particular, with a resolution of <math><5\text{--}10\text{ yr}</math> allow to explore high frequency decadal to multi-centennial variability. To reduce noise, smoothing has been applied.

2. Results

Multi-proxy time series (figure 2) suggest that major mid-Holocene climate reorganisation on the southern Iberian Peninsula went along with major social transformations. SE and SW ensembles, marine climate variables, speleothem records as well as the records of human activities show large fluctuations on millennial to multi-decadal scale over the entire course of the 3000 yr time window. The long-term trends in both archaeological and environmental variables are superimposed by fluctuations of multi-decadal to centennial time scales. While the climate variables in the long run generally show similar cooling and drying condition trends in the western and eastern sectors, respectively, differential SW

and SE trajectories of human activities are evident over time.

2.1. Climate variability on the southern Iberian Peninsula

The ensembles of stacked *z*-scored records of annual and winter precipitation and of annual temperature in light of the SW and SE high-amplitude variability and decadal to centennial scale superimpose long-term cooling and drying trends. The ensembles of precipitation records as well as the lower resolution marine *n-alkane* records reasonably well match the variability of the high-resolution (ca. 2–4 yr) speleothem records (monitoring annual precipitation). Precipitation records overall suggest similar variability in the SW and SE with major rapid transitions at 5300, 4800, 4440, and 3800 cal yr BP (figures 2(A)–(E)). In addition to an earlier interval of enhanced climate instability from ca. ~5700 to 5200 cal yr BP, an interval of pronounced precipitation variability is reported between 4400 and 3800 cal yr BP, generally related to the 4.2 kyr BP event. In our records, it was marked by overall gradually decreasing precipitation values and prolonged events of maximum amplitudes. This is particularly distinct in the two speleothem records of El Refugio (Walczak *et al* 2015) and Buraca Gloriosa (Thatcher *et al* 2020) (figure 2(D)). The ensembles of precipitation records during this interval show a gradual decrease in winter precipitation with

largest fluctuations in annual precipitation in winter, in particular (figures 2(A) and (B)), which were more pronounced in the SE. The marine *n-alkane* records (figure 2(E)) indicate two distinct dry events bracketing an interval of relatively moister conditions. These events appear more pronounced in the SW, a pattern well constrained by the ensembles of *z*-scored winter records, otherwise marked by pronounced oscillations between dry and humid excursions.

Annual temperature reconstructions, based on fewer records ($n = 8$ in the SE, and $n = 6$ in the SW) and thus to be considered as less robust, reveal a complex pattern of short-term variability. Two longer cooling episodes are reported by the SE ensemble paralleling the intervals of drier conditions. Marine records based on planktonic foraminifera assemblages suggest cool winter SST of 15 °C in the Alboran Sea (figure 2(F)). In contrast, in the SW only the earlier interval is paralleled by cooling SST records in the SW/Gulf of Cadiz, which reveals a distinct and rapid shift towards altered seasonality from 4000 cal yr BP onwards. Accordingly, summer to winter contrasts increased in the SE during that period, yet at the same time they decreased in the SW.

2.2. Changes in human activities

A pronounced asymmetry of the eastern and western activity trajectories is evident in the SPDs over time, suggesting major ‘boom and bust’ cycles distinctly out of phase. Patterns start to diverge particularly after 4400 cal yr BP, suggesting partially antidromic developments of human activities in both regions (figure 2(G)). While in the southwest, an early increase in activities starting around 5700 cal yr BP is disrupted by a 200 yr reversal, well paralleling a period of cooling and drier conditions (figures 2(A) and (F)), subsequent activity levels stepwise and steadily increase culminating around 4800 cal yr BP. The aoristic settlement pattern (figure 2(H)), as only available for the SW, well supports the SW SPD patterns (Hinze *et al* 2019). Maximum settlement activities in Southern Portugal are shown from 4750 to 4250 cal yr BP (corresponding to the regional archaeological phases of the Initial to the Final Chalcolithic) with a culmination during the later phases. In the transition from the Chalcolithic to the Early Bronze Age, settlement activities dramatically dropped. In the SPDs, this decline started around 4500 cal yr BP with a sharp and subsequent more gradual decline lasting until ~3300 cal yr BP. This pattern is well paralleled by the onset of a gradual decrease of precipitation values. High temperature variability is marked by winter cooling events (figures 2(C) and (F)), whereby the

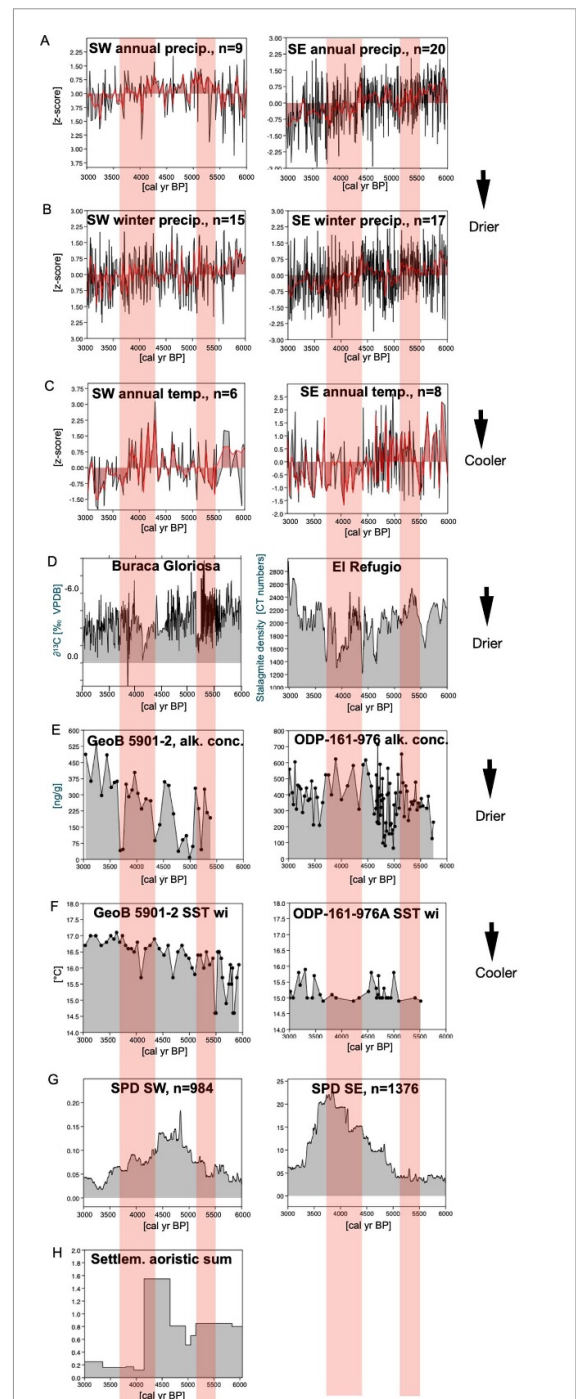


Figure 2. Multi-proxy time series of climate and archaeological variables records from the southwestern (left panels) and southeastern (right panels) Iberian Peninsula. (A), (B) Ensembles of *z*-scored annual and winter precipitation records; (C) ensemble of *z*-scored annual temperature records (from Schirmacher *et al* 2020); (D) speleothem records from El Refugio cave (density data from Walczak *et al* 2015), and La Buraca Gloriosa ($\delta^{13}\text{C}$ data from Thatcher *et al* 2020; available through NOAA paleodata); (E), (F) marine precipitation and sea surface temperature (SST) records based on *n-alkane* concentrations; winter temperature based on planktonic foraminifera assemblages (from Schirmacher *et al* 2019) with adjusted age models from Schirmacher *et al* 2020), (G) SPD records used as proxy for intensity of human activities (from Hinze *et al* 2019); (H) aoristic record of settlement numbers in southern Portugal.

low resolution SST record suggests winter cooling by -2 °C. A recovery of human activities is registered only during the LBA with a preceding transient recovery during the Middle Bronze Age, evolving under relatively inconspicuous climate conditions.

In the SE, Chalcolithic activities started with a relative delay of approximately 500 yr around 5000 cal yr BP as compared to the SW (figure 2(G)). Afterwards, they steadily increased until 3800 yr BP, an initially inert trend and superimposed by minor halts and a backslide. This phase is followed by a sharp increase at \sim 4100 cal yr BP, and a further step of rapid increase around 3900 cal yr BP. High levels lasting for some 600 yr reflect the boom of the El Agar culture in the area, as well-documented to have evolved in two phases (Lull *et al* 2011, 2013). Notably more convergent SE and SW trajectories of activities are reported between 5000 and 4400 cal yr BP, corresponding to a boom phase of Los Millares cultures.

These changes in human activities were paralleled by profound cultural shifts as indicated by changes in material culture (figure 3(A)) and by the detailed archaeological record of the Andalusian mega-site Valencina de la Concepción, located at the eastern margin of the SW region (figures 1 and 3(B)). To ease comparison of archaeological and environmental trajectories in the SW and SE regions, in the SW and SE regions, the E–W gradients of selected variables between these areas are displayed in figures 3(C) and (D). Aoristic abundances of exotic ivory and amber items in Iberian archaeological inventories are calculated for 100 yr steps (figure 3(A)), as considered to particularly reflect changes in the Iberian networks (Murillo-Barroso and Martín-Torres 2012, Schuhmacher 2012). A contemporaneous increase of ivory and amber items is considered to have reflected the establishment of long distance networks after 5100 yr BP with an intensification after 4100 yr BP, culminating around 3800 yr BP, as particularly evident in a brief increase of ivory items. Coevally with the decline of ivory and amber around 4100 yr BP, the abundance of daggers (with some 20% representing SW finds) started to boom at \sim 3750 yr BP and culminated during the MBA.

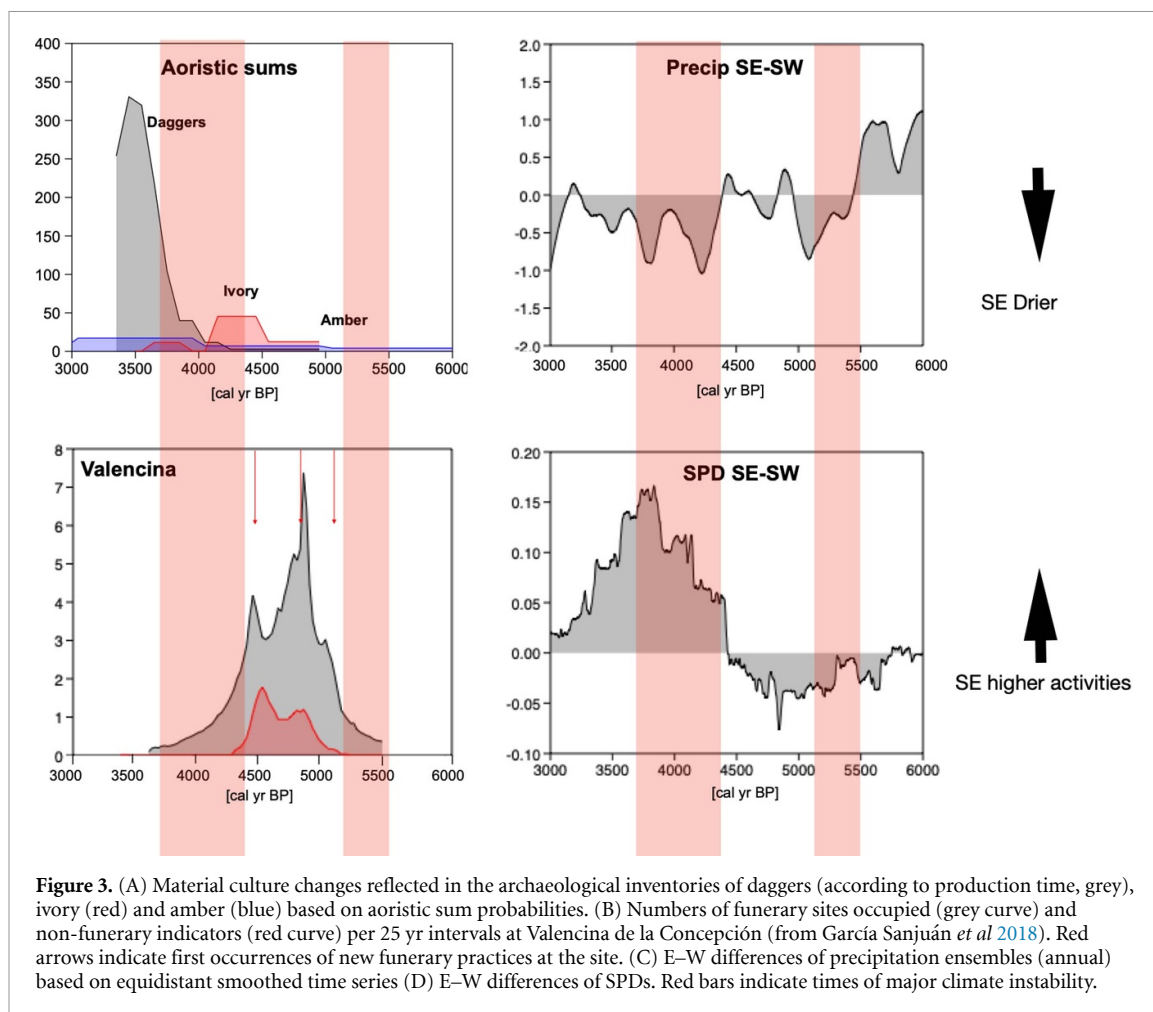
At Valencina within an overall 2000 yr record, major funerary activities are monitored evolving from 5200 to 4300 cal yr BP, double peaking around 4850 yr BP and well matching SW SPD patterns. The non-funerary record shows a double peak of maximum activities at the site as well, with the first peak preceding the funerary curve by \sim 100 yr. It is noteworthy to mention that this site in our SW SPD data base is only represented by a sample of 21 ^{14}C data. Both chronologies are thus widely independent.

The E–W gradients of human activities involve a shift of activities from W to E along with a tendency towards more pronounced dry spells in the SE. Within temporal resolution and dating accuracy, these changes appear intimately linked to changes

in the intensity of human activities. A tipping point when the focus of the southern Iberian trajectories shifted from west to east is pinpointed around 4400 cal yr BP, matching the onset of drier conditions in the SE.

2.3. Time series analyses

Both the climate and the societal records over the course of the 3000 yr interval explored here show high-frequency oscillations superimposed to long-term patterns. Different from the climate time series, where short-term variability generally exceeds the amplitudes of the long-term trends, the patterns of human activities are dominated by long-term cycles that are modulated by secondary fluctuations of lower amplitude. Here, short-term oscillations superimpose long-term patterns that correspond to time-lagged boom and bust cycles in the SW and SE, each of \sim 1500–2000 yr duration. In the frequency domain, detrended time series of societal and environmental variables reveal a broad range of significant power maxima indicating periodic oscillations in the range of multi-decadal to multi-centennial scales (figure 4). Spectra of similar periods occur in all environmental and archaeological variables, but are rarely identical for the individual variables (as expected in untuned time series from a variety of archives, proxies and age models). Nonetheless, the individual spectra concentrate power in defined frequency bands. A common forcing or a similar rhythm of different forcings is thus suggested, modulating the social and environmental time series. In contrast, the lower resolution and unevenly sampled marine climate records (in average solving 20–70 yr) are less suitable to explore cycles in that range. In the frequency domain, the records show particularly significant power in the frequency bands ranging from 0.001 to 0.006 (figure 4). Moreover, fewer and less distinct peaks are revealed in the SW, probably due to the generally lower resolution and less well constrained age models of the individual records. The high-resolution El Refugio cave (Walczak *et al* 2015) and Buraca Gloriosa speleothem records (Thatcher *et al* 2020), both with age models relying on U/Th datings, cover the 3000 yr window continuously with an average temporal resolution of 2–4 yr. Both in the frequency domain, they reveal a suite of peaks corresponding to \sim 600–200 yr periods, with dominant power around periods of 250 and 190 yr as well as further maxima in the higher high-frequency range with periods $<$ \sim 170 yr (figure 4(D)). The SE ensembles show maxima in the range of 290–160 yr-periodicities with outstanding peaks of 200 and 220 yr (annual precipitation, figure 4(A)), 172 (winter precipitation, figure 3(B)), and 160 (annual temperature, figures 4(A)–(C)). These are however, different from the Buraca Gloriosa record, not developed in the other SW climate records. In contrast, peaks in the lower frequency range of 378 are shown by



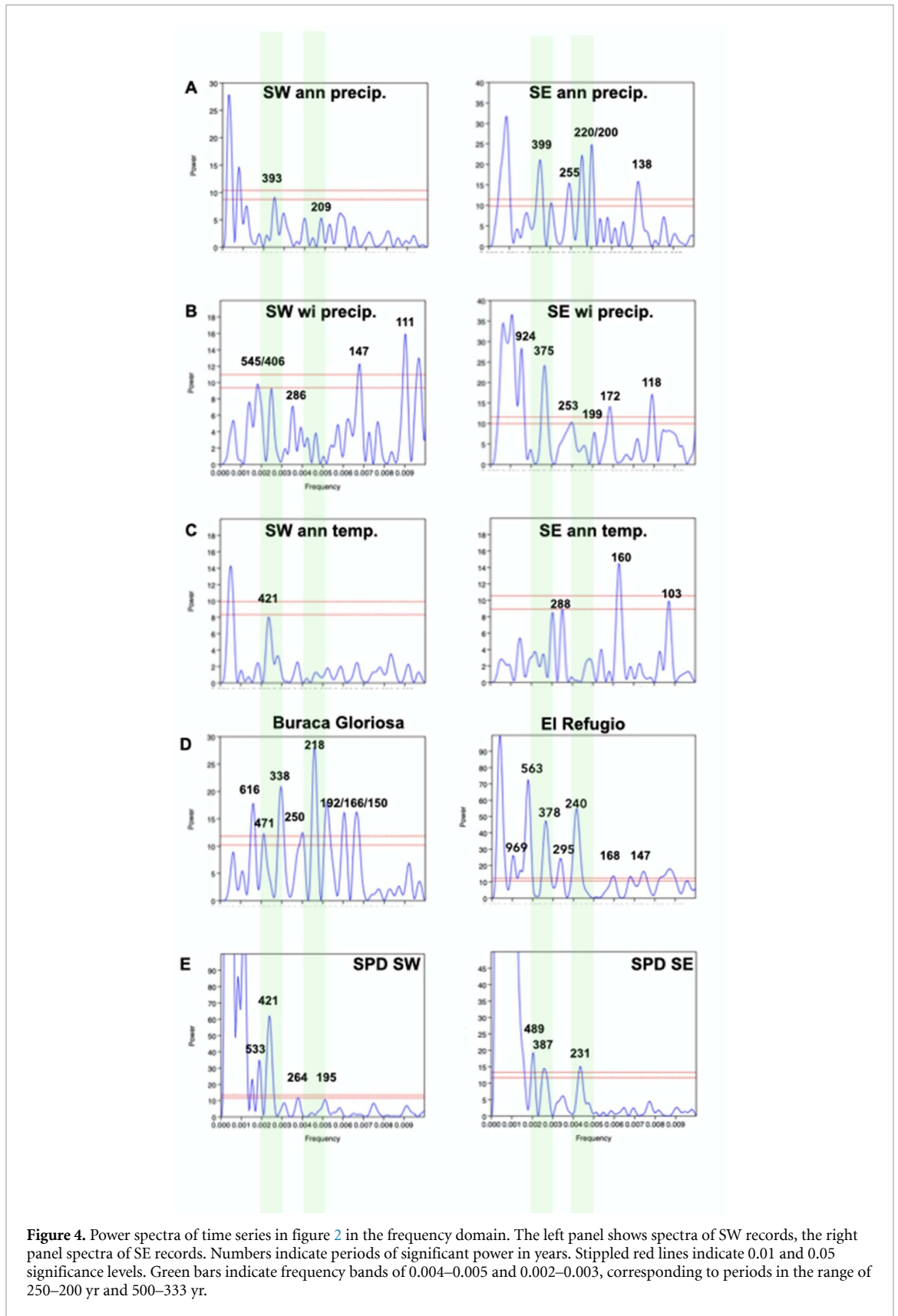
the ensembles in both areas, for both precipitation and temperature records, here resembling the patterns of the speleothem records. The spectra of the SPD time series (figure 4(E)) show a similar spectrum of power in the SW and in the SE with periodicities of 390–490, and of 200–230 yr. These resemble the spectra of the climate variables. No significant differences were found when separately exploring intervals of 4500–3000 and 6000–4500 yr BP (spectra not shown; SW: 444(419), 200/235(218), 160(160); SE: 270(280); 230(235)). Periodicities of ~200/400 yr are typically related to de Vries/Suess cycles (average period 208 yr), resulting from variable sun spot activity and present in many Holocene climate records.

3. Discussion

Our reconstructions underline that the mid-Holocene on the Iberian Peninsula was a time of socio-environmental turnover with complex interactions of pre-state societies and their environments. Time series of climate changes over the course of a 3000 yr time span from the mid- to Late Holocene feature two intervals of marked instability (~5700–5300 cal yr BP and ~4400–3800 cal yr BP), the latter generally related to the 4.2 ky BP event

(Bini *et al* 2019). A hazard for Agrarian Chalcolithic and Early Bronze Age communities must have been constituted under enhanced North Atlantic climate forcing, alternating episodes of reduced winter precipitation. These were marked by winter coolings and higher seasonality, as well as hot and moist conditions, when transitions occurred within a decade and draught episodes sometimes lasted for decades. Increasing environmental stress with impacts on vegetation cover, soils, and agriculture are well-known from numerous palaeobotanical studies available for the region. Phases of widespread decline of arboreal pollen in the (western) Mediterranean pollen archives (Zanon *et al* 2018), paralleling these intervals, suggest that forest decline was a result of reinforcing effects of human land use activities and draught.

‘Boom and bust’ cycles of human activities (likely also reflecting demographic patterns) on the Iberian Peninsula evolved against this background of climate deterioration with more severe impacts in the SE and differential and time-lagged trajectories in the western and eastern sectors. SPDs reveal sequential patterns of surges, plateaus, sharp declines, and recovery. This pattern can be well related to phases of growth/exploitation, conservation, release, and reorganisation, corresponding to the four adaptive phases and



resilience levels according to Bradtmöller *et al* (2017).

Phases of rise and expansion of the Los Millares culture, the long and continuous Chalcolithic occupation phase of the Portuguese ditched enclosures,

and the rapid rise and 600 yr record of the El Argar culture all partially occurred under preponderantly unfavourable climate constraints (figures 2 and 3) and considerable environmental stress, thus attesting the high resilience of these societies against external

disturbances. In particular, the rise of the El Argar culture had considerable momentum and culminated (3800–3400 cal yr BP) in a phase of severe climate deterioration (figure 4), marking the major tipping point in our records related to the 4.2 ky BP event, when the southwest communities were in rapid descent. The rapid onset of a climate regime leading to enhanced draught and pronounced seasonality with cool winters appears to be related to a rapidly decreasing influence in Mediterranean-sourced moisture (Schirrmacher *et al* accepted). This pattern suggests a high exposure of people living in the southeast.

In this context, sophisticated water management strategies, draught resistant barley monocultures, central policies regulating the distribution of and access to resources, food storage systems, and labour division together with the regulation of socio-environmental stress through socio-political and socio-cultural strategies fostering connectivity may well be interpreted as adaptive strategies to successfully cope with environmental change and increasing demographic stress. A multitude of such evidence is reported in archaeological narratives and data for the Early Bronze Age, but also for earlier time spans (e.g. Lull *et al* 2011, 2013, 2015, García Sanjuán and Murillo-Barosso 2013, Valera *et al* 2015, García Sanjuán *et al* 2018, Valera 2020; and for syntheses Blanco-González *et al* 2018). Yet, more statistically solid evaluations with a supra-regional and long-term view are awaited. Here they nicely underline our results. This evidence may also imply that the pre-state societies were well aware of the risks of climate and environmental change.

Only after several centuries, failures of these highly efficient strategies are evident under increasing climate stress. The widespread abandonment/collapse of Chalcolithic mega-sites in Southern Portugal as well as the end of the El Argar culture may have been induced and/or accelerated by parallel severe climate events. The ‘collapse’ of megastructures in the SW coincided with the phase of rapid climate reorganisation and may be well explained by a lack in resilience of the Chalcolithic economies against repeated failures of winter precipitation. The progressive decrease of activities in the SW started with a sharp decline at ~4400 yr BP. Arguably (because of a dependency on precise age models), signs of erosion of cultural developments preceded this final ‘collapse’ (e.g. manifested in a decrease in the quality of ceramic production (Ribeiro, unpublished data) and the abandonment of ritual practices (García Sanjuán *et al* 2018), reflecting a gradual decline in the intensity and quality of cultural activities (Valera 2015). Though poorly dated, this evidence preceded the SPD and the environmental deterioration, perhaps reflecting a preceding decay of resilience and connectivity. Subsequent to this initial drop, activities decreased steadily and inexorably until reaching stable minimum values, a trend merely counteracted

by some halts and weak reversals. A similar pattern is evident in the well-dated record of the Andalusian mega-site Valencina de la Concepción. Here, a trajectory paralleling the decline of SW activities is well constrained by the coeval cessation of funerary activities. In addition, distinct changes in funerary practices underline the cultural and ideological changes that the site underwent. Notably, the record of the non-funerary activities at the site peaking at 4600 yr BP/2650 BCE predate the funerary activities by ~200 yr (figure 3(B)).

The ‘decline’ of the El Argar culture briefly after its maximum boost phase, and eight centuries after the SW ‘collapse’, evolved similarly with an initial sharp decline and further phases of rapid decline over the course of ~300 yr. It was preceded by a marked draught and cooling event as reported by the El Refugio record and the SE ensembles (figure 2), marking the beginning of a phase with a new level of reduced precipitation levels with yet warmer temperatures. Thus, it again appears plausible that reinforcing effects of climate, environmental degradation and demographic stress rapidly brought the system to its limits. The preponderance of cereal cultivation in extensive dry land farming in this context is considered a risk to economic strategies depending on a limited number of resources and reduced biodiversity (Lull *et al* 2013).

The consequences of these socio-environmental ‘collapses’ in both cases were long lasting. The recovery of human activities are first registered only centuries later despite more stable climates. Our results further support hypotheses that rapid climate change may constitute a particular risk under high demographic pressure as postulated by Turchin and Nefedov (2009), based on an array of historical scenarios where similar patterns applied. In such constellations, climate-driven environmental degradation is reinforced by human induced environmental degradation thus accelerating a decay of resilience and rapidly reaching socio-environmental thresholds.

When comparing Iberian trajectories in the SW and SE (figures 3(C) and (D)), a main tipping point is pinpointed at 4400 BP/2250 BCE. Thereupon, the focus of human activities shifted from SW to SE, matching the onset of the Mediterranean climate in the SE. The anti-phased patterns of human activities on the southwestern and southeastern Iberian Peninsula along with major transformations and rapid and profound social and cultural turnover (figure 3) raises questions whether these patterns may be explained by large-scale population displacements from west to east. According to an IOM report (2020), significant population movement can be evidence of instability depending on the type of mobility. Displacement population movement is interpreted as an indicator of the breakdown of social resilience. While our SPD records of human activities do not provide any further clue on the mechanism responsible for the observed

large-scale shift of human activities (as probably also related to changes in population density), we can only speculate whether enhanced inner Iberian or western Mediterranean migration may have contributed in shaping the regional boom and bust patterns on the southern Iberian Peninsula. So far, aDNA studies provide little information on possible western Mediterranean migration activities (Olalde *et al* 2019). If the observed climate deteriorations triggered a major migration wave on the SW Iberian Peninsula, the origin and whereabouts of the people remain unclear. In the case of SW trajectories, it appears unlikely that refugees chose an area where climate conditions were even more hostile, making the idea of 'climate refugees' invading SE territories less compelling. Movements from the pre-urban centres into rural regions are an alternative explanation, yet difficult to trace with existing data. A decay of large settlement centres previously concentrating major activities with the establishment of subsequent more dispersed settlements have been shown by Hinz *et al* (2019). The latter are, however, underrepresented in the archaeological record, thus necessarily underestimating the rural population fluctuations. In the case of El Argar, increased conflict and warfare have also been invoked as strategies to cope with socio-environmental stress that could have impacted absolute population levels. The vast increase of daggers produced during the final phases of the El Argar culture in addition to heavily fortified El Argar settlements may hint in this direction (Brandherm 2003, Aranda-Jiménez *et al* 2009, Lull *et al* 2015).

Apart from the outlined long-term patterns, our records also show variability on shorter scales. The presence of significant de Vries-like periodicities (a ~ 200 yr oscillation) in the spectra of both palaeoenvironmental and societal variables suggests recurrent cycles of socio-environmental instability (~ 160 – 250 yr periods, figure 4), ultimately forced by periodic climate disturbances. Moreover, longer periodicities in our records of 300–500 yr duration may constitute subharmonics of the de Vries cycle. A broad array of northern hemispheric proxy data sets shows climate impact of this cycle related to solar activity and terrestrial ^{14}C production. A mid-Holocene interval from 5700 to 4500 cal yr BP has been found to display particularly strong de Vries cyclicity (Knudsen *et al* 2011), modulating monsoonal precipitation patterns monitored in subtropical speleothems. A climate forcing may indeed explain the presence of such periodicities in the SPD time series at the interface of subtropical and North Atlantic climate constraints. Yet, it is also conceivable that social mechanisms modulated archaeological cycles of multi-centennial scale duration, involving socio-economic, socio-political and socio-cultural factors. Turchin and Nefedov (2009) outlined historical scenarios and processes exhibiting recurrent patterns of change, including century-long periods of population

expansion preceding long periods of stagnation and decline as well as economic variables mirroring population oscillations. Assessing the role of ENSO climate variability in exerting stress on people found reduced source availability and increasing human populations most reinforcing factors in many Holocene archaeological scenarios (Anderson *et al* 2007). Siegmund (2013) explored the absolute duration of individual phases of archaeological chronology systems based on material finds. In particular, he found that long phases (80–175 and >175 yr) particularly marked times of the introduction of major technological innovation, such as the beginning of the Bronze Age, i.e. periods with fewer changes in the material culture. Recurrent cycles in human activities on the Iberian Peninsula may be interpreted in terms of cycles of increasing and decaying resilience, modulated by climate. In their study of early farming societies in SW Central Europe, Gronenborn *et al* (2017) found that time-lagged patterns of diversity and population size as well as severe climate excursions shaped the location of tipping points in the social system. On the Iberian Peninsula, centennial-scale variability marked both boom and bust patterns (considered to reflect cycles of decay and growth of resilience) in both southern sectors of the Peninsula as well as the time windows prior to and after the 4.4 ky tipping point. Regardless of the pronounced cultural differences marking the four scenarios (e.g. Blanco-González *et al* 2018), similar variability persisted under different socio-cultural developments. Hence, a persistent level of instability appears inherent to socio-environmental systems. Thus far, our time series analyses are not precise enough (i.e. spectra are not sharp enough) to explore phase relationships between different socio-economic and environmental variables or to identify potential sequences of broader validity and to determine response times within these systems. Yet at this point, our study underlines that mid-Holocene social and environmental processes are closely coupled at various scales, and justify an interpretation of the occurrence of socio-environmental cycles.

4. Conclusions

Regionally stacked climate records and archaeological variables provide valuable time series to empirically test hypotheses of socio-environmental dynamics and the development of resilience on a long timescale, in particular when combined with evidence of material culture. Our results lend robust support to hypotheses indicating that mid-Holocene climate changes, environmental shifts and social trajectories at the transition from the Chalcolithic to the Early Bronze Age were intimately linked.

Two phases of enhanced climate instability occurred from ~ 5700 – 5200 BP to ~ 4400 – 3800 yr BP,

interfering with boom and bust cycles of human activities and reflecting resilience changes.

The continuous rise and boost of Chalcolithic cultures on the SW Iberian Peninsula and the EBA El Argar culture in the SE during these intervals indicate high resilience of these societies during the earlier phases.

A decay of resilience is suggested along with culminating and reinforcing effects of enhanced climate stress, environmental degradation and population growth, which initiated phases of sharp decline. These were preceded by cultural changes as reflected in material culture, indicating reorganisation of exchange networks together with ideological changes.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

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Author contributions and responsibilities

M Weinelt wrote the manuscript based on discussions and contributions with and by the co-authors from archaeology and marine paleoclimatology. She provided the marine temperature records, and performed the time series analyses; J Schirmmayer provided the data base of SW and SE ensembles, and the marine precipitation records; J Kneisel provided archaeological expertise, and compiled and processed the archaeological data of material culture using aoristic methods; A Ribeiro helped with his expertise on SW Iberian archaeological changes; M Hinz compiled and tested the SPD data base, and provided the aoristic settlement approach.

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