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The influence of climatic change on the Late Bronze Age Collapse and the Greek Dark Ages

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ABSTRACT

Between the 13th and 11th centuries BCE, most Greek Bronze Age Palatial centers were destroyed and/or abandoned. The following centuries were typified by low population levels. Data from oxygen-isotope speleothems, stable carbon isotopes, alkenone-derived sea surface temperatures, and changes in warm-species dinocysts and formanifera in the Mediterranean indicate that the Early Iron Age was more arid than the preceding Bronze Age. A sharp increase in Northern Hemisphere temperatures preceded the collapse of Palatial centers, a sharp decrease occurred during their abandonment. Mediterranean Sea surface temperatures cooled rapidly during the Late Bronze Age, limiting freshwater flux into the atmosphere and thus reducing precipitation over land. These climatic changes could have affected Palatial centers that were dependent upon high levels of agricultural productivity. Declines in agricultural production would have made higher-density populations in Palatial centers unsustainable. The 'Greek Dark Ages' that followed occurred during prolonged arid conditions that lasted until the Roman Warm Period.

1. Introduction

At the end of the Late Bronze Age (LBA) most Eastern Mediterranean urban centers were either destroyed or abandoned throughout the Near East and Aegean (Andronikos, 1954; Vermeule, 1960; Desborough, 1964; Carpenter, 1966; Weiss, 1982; Iakovides, 1986; Neumann and Parpola, 1987; Alpert and Neumann, 1989; Mazar, 1990; Beckman, 2000; Dickinson, 2010). This period of dissolution begins in the Late Helladic (LH) IIIB (1315–1190 BCE) and is complete by the end of the LH IIIC (1050 BCE). The following four centuries are typified by rural settlements, population migration, and limited long-distance trade, a period termed the 'Greek Dark Ages' for the Aegean region. The LBA collapse is associated with the loss of writing systems such as Linear B (Palaima, 2010), and the extinction of Hatti as both a written and spoken language (Fortson, 2004). Writing and literacy do not return to the Aegean until the end of the 'Greek Dark Ages' in 8th century BCE with the spread of the Phonecian alphabet (Sass, 2005).

For decades theorists have developed hypotheses to explain the drastic changes in settlement patterns at the end of the LBA. They can be divided into three broad classes: economic, military, and climatic explanations. Recently, Kaniewski et al. (2010) have suggested that a centuries-long megadrought caused the widespread systems collapse of Bronze Age Palatial civilization. This hypothesis is testable as such a drought should be reflected in multiple climate proxies available for the time period.

This paper will review existing arguments for the LBA collapse alongside paleoclimate proxy records, including:

i) paleorainfall derived from stable oxygen-isotope speleothem records,
ii) stable carbon isotope chronologies from pollen records in Greece
iii) alkenone sea surface temperatures (SSTs) derived from Mediterranean sediment cores,
iv) warm/cold species dinocysts and formanifera from Mediterranean sediment cores,
v) paleotemperature proxies derived from Greenland ice cores, and
vi) solar irradiance data derived from cosmogenic Beryllium (^{10}Be) in ice cores.

2. Archaeology of the Late Bronze Age Collapse

The collapse of Palatial Civilization at the end of the Bronze Age (1315–1190 BCE) occurred in different places at different times over the course of two centuries. Many of these destructions have been

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attributed to human-causes. Large population migrations took place, most famously with the incursions of the 'Sea Peoples' into the Nile Delta and the Levant (Sandars, 1987). Following this period, societies of the Eastern Mediterranean enter into a long-term decline. By 1050 BCE, most urban centers had been abandoned. In the Aegean region the following 350 years are known as the 'Greek Dark Ages', where low population levels lead to little archaeological visibility (Desborough, 1964).

In Egypt, several inscriptions detailed wars with 'Sea People' from the Nile Delta to the Levant beginning in the reign of Ramses II (1279–1213 BCE). In the southern Levant, pottery began to resemble Mycenaean types, but analysis suggests that they were locally produced, suggesting a population migration from the Aegean region to the coastal Levant (Mazar, 1990). While the population movements of the 'Sea People' were better documented in Egypt and the Levant, they has been tied to destabilization of the Aegean region as well (Beckman, 2000). The label of 'Sea People' is broad, and likely covered many ethnic groups, including many that were of Greek origin (Chadwick, 1976). Large population movements and the possible use of mercenary military forces had a destabilizing effect on the economy (Vermeule, 1960). Andronikos (1954) argued that the destructions during this time period could reflect rebellion along different class lines. Regardless of the source of the destructions, with trade relationships broken down it was difficult for leaders to maintain control over their local districts. This economic decline resulted in the widespread dissolution of polities (Iakovides, 1986). Once the polities were dissolved it was impossible to reestablish a central authority (Betancourt, 1976; Hutchinson, 1977).

While economic systems collapse continues to be the dominant perspective of the collapse of Palatial Civilization in the Bronze Age (Iakovides, 1986), climatic/environmental explanations have also been proposed. Carpenter (1966) was the first to propose a drought as the cause of the dissolution of Mediterranean Palatial Civilization. Atmospheric circulation patterns that could have resulted in a short-term drought may have been present during the Late Bronze Age (Bryson et al., 1974). Weiss (1982) found that the entire Eastern Mediterranean could have been struck by climate anomalies under the circulation patterns proposed by Bryson and colleagues.

An important consideration is the effect of earthquakes in the region. Schaeffer (1948, 1968) proposed that tectonic instability in the area could have been responsible for the simultaneous abandonment of cities in the Eastern Mediterranean. Earthquakes in the region tend to occur in clusters, and a series of earthquakes over one or two generations could have contributed to the destabilization of several polities (Nur, 1998; Nur and Cline, 2000). Many destruction layers indicate earthquake-caused damage (Nur and Cline, 2000).

3. Paleoclimate

Discussions of climate and the end of Palatial Civilization in Greece have focused on Carpenter's (1966) proposed drought event (Bryson et al., 1974; Weiss, 1982). Kaniewski et al. (2010) were the first to identify a shift in climate as a factor in the changes at the end of the Bronze Age. At the site of Giala-Tell Tweini in Syria they identified the period between 1200 and 850 BCE as one of prolonged drought through pollen and alluvial records. Issar (2003) also argued that the migrations of the Late Bronze Age/Early Iron Age were the consequence of heightened aridity. More recent work also suggests arid conditions for the same time period (Mayewski et al., 2004; Finné et al., 2011) (Fig. 1).

Three additional lines of evidence suggest a prolonged arid period in the Eastern Mediterranean at the end of the Late Bronze Age and into the Early Iron Age. The first comes from oxygen-isotope speleothem data from Soreq Cave in Northern Israel (Bar-Matthews et al., 1998, 2003) which indicates low annual precipitation during the Late Bronze Age/Early Iron Age (LBA/EIA) transition. The second is derived from stable carbon isotope data in pollen cores from Lake Voulkaria in Western Greece (Jahns, 2005) which record a drop in ^{13}C discrimination during this period. The third is a series of Mediterranean sediment cores that record a drop in surface sea temperatures (SST) (Emeis et al., 2000) and a reduction in warm-species dinocysts (Rohling et al., 2002; Sangiorni et al., 2003).

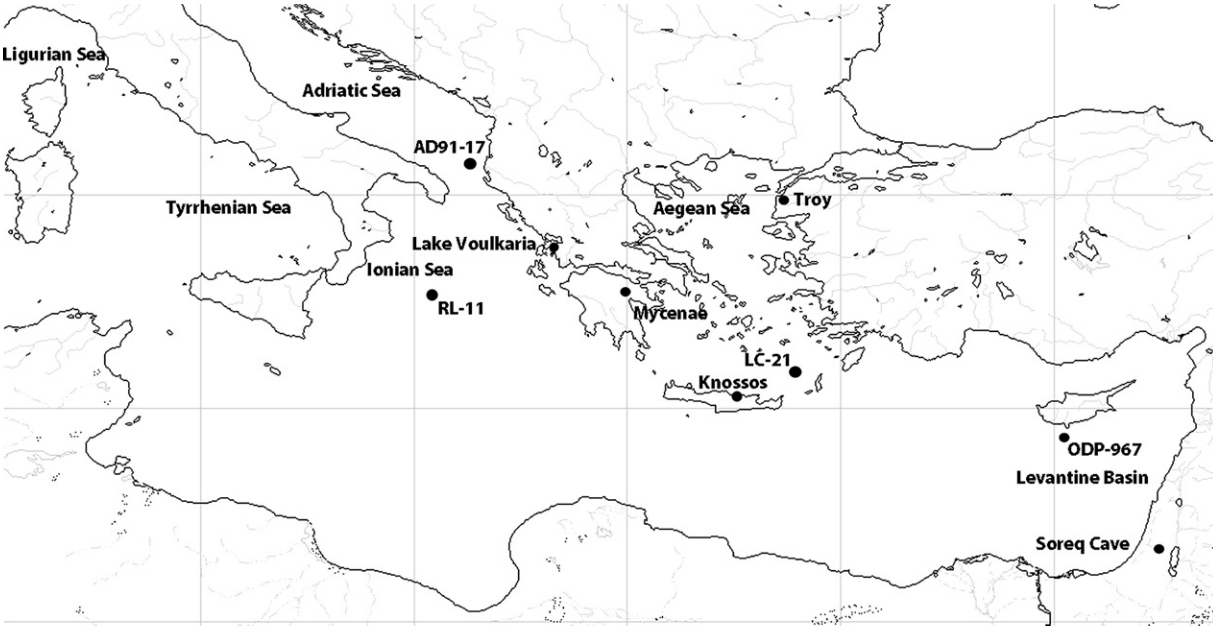

Fig. 1. Map of Eastern Mediterranean, including sediment core locations (Emeis et al., 1998; Emeis et al. 2000; Rohling et al., 2002), oxygen-isotope speleothem records from Soreq Cave (Bar-Matthews et al., 1998; Bar-Matthews et al. 2003), and stable carbon isotope values from Lake Voulkaria (Jahns, 2005).

3.1. Stable oxygen-isotope speleothem records

Soreq cave in Israel contained a 150,000 year record of precipitation for the northern Levant (Bar-Matthews et al., 1998; Bar-Matthews et al., 2003). Reconstructed paleorainfall from Soreq document three severe drops in precipitation during the Holocene. The first two were consistent with known climatic events: the Younger Dryas and an aridization event at 3150 BCE associated with widespread erosion in the Middle East and spikes in dolomite and calcium carbonate concentrations in the Gulf of Oman (Bar-Matthews et al., 2003; Cullen et al., 2000). The third decline in precipitation occurred at 1150 BCE, contemporaneous with the recently proposed multi-century drought in the Levant (Kaniewski et al., 2010).

3.2. Plant stable carbon isotopes

Recent research has shown that the discrimination against ^{13}C in C_3 plants varies due to mean annual precipitation (Diefendorf et al., 2010). This relationship appeared to be the consequence of plant adaptations to arid environments. C_3 plants in arid regions are more conservative with their water use and this is reflected in their discrimination against $\delta^{13}C$. The implication of research in stable carbon isotopes is significant for archaeological data. As radiocarbon dating procedure requires the reporting of $\delta^{13}C$ values (Stuiver and Polach, 1977), there is potential to identify paleoclimate signals in data already gathered by archaeologists. Riehl and colleagues (2008) examined carbon discrimination in barley plants in Anatolia, and found lower rates of discrimination at 2250 BCE and 3150 BCE – both significant short-lived aridization events in the broader region (Bar-Matthews et al., 2003; Cullen et al., 2000).

Stable carbon isotope data from C_3 plants tend to be highly variable, and can be influenced by factors other than water availability (Seibt et al., 2008). Recently, the use of "representative" stable carbon isotope values has been suggested (Leavitt, 2008); a procedure in which data from multiple plants is aggregated to highlight a broader climatic signal. Theoretically, this procedure could be done on stable carbon isotopes from radiocarbon-dated pollen. This data would produce representative stable carbon isotope values for a region. Rather than reflect specific droughts, this data could reflect the spread of plants adapted to arid regions, the kind of broad biome data used by Diefendorf et al. (2010).

3.3. Surface sea temperatures

The temperature of surface sea water governs evaporation rates, which in turn affect the amount of moisture available to storm systems. The sea level freshwater flux (E – P, evaporation minus precipitation) provides the strongest input to the Mediterranean region's hydrological cycle (Mariotti et al., 2002). Most precipitation in the Eastern Mediterranean comes during the winter, when the cold and dry westerlies sweep in and absorb water vapor evaporating from the warmer Mediterranean (Issar, 2003). From 1979–1993, the peak evaporation rate in the Mediterranean occurred in December with 1500–1600 mm/yr of water taken up by the westerlies. That same month the Mediterranean region experienced precipitation maxima, at 800–900 mm/yr (Mariotti et al., 2002). The lowest evaporation rates (600–700 mm/yr) in May/June were followed by precipitation minima in June/July (100–200 mm/yr). In the Mediterranean, precipitation over land is constrained by water evaporating from the sea. In turn, evaporation in the sea is constrained by temperature differentials between the sea and surface air. Lower sea surface temperatures (SSTs) depress evaporation by reducing the temperature difference between the warmer sea waters and cold winter air. Changes in Mediterranean SST have been linked to precipitation cycles in Anatolia (Kwiecien et al., 2009; Bozkurt and Sen, 2011) and in the Sahel (Rowell, 2003). In both cases, warmer SST's led to saturation of the troposphere and increased precipitation during rainy seasons.

Past sea surface temperatures can be estimated from lipids using the alkenone unsaturation index (Brassell et al., 1986) derived from date modeled layers in marine sediment cores. Faunal and isotopic analysis can also be used to estimate major changes in SST (Rohling et al., 1993), as many species are constrained to warm or cold water. Multiple sediment cores in the Eastern Mediterranean form a 400,000 year record of SST variations (Emeis et al., 1998, 2000). Time-series temperature records exist for the Ionian Sea, Levantine Basin, and Adriatic Sea throughout most of the Holocene (Cacho et al., 2000). Records of warm-species dinocysts and formanifera are available from the Adriatic and Aegean seas, respectively.

4. Methods

4.1. Terrestrial records

Stable carbon isotope values from radiocarbon-dated pollen from a sediment core in Voulkaria Lake in Western Greece (Jahns, 2005) were used to calculate ^{13}C discrimination ($\Delta^{13}C$) values following standard procedures (Farquhar et al., 1982; Farquhar and Richards, 1984):

$$\Delta^{13}C = \delta^{13}C_a - \delta^{13}C_p/\left(1 - \delta^{13}C_p/1000\right)$$

where $\delta^{13}C_a$ represents atmospheric $\delta^{13}C$ values of CO_2 and $\delta^{13}C_p$ represents plant $\delta^{13}C$ values. Carbon discrimination values developed from radiocarbon pollen represent biome-level carbon discrimination, rather than the activities of specific plants. Values for $\delta^{13}C_a$ came from the European Project for Ice Coring in Antarctica (EPICA) (Elsig et al., 2009). An average value of $-6.36‰$ was used to calculate $\Delta^{13}C$ at 538 BCE, as data from EPICA shows evidence for modern contamination via an ice core break as reported by the investigators (Elsig et al., 2009), though resulting $\Delta^{13}C$ values are only decreased by 0.79‰.

The carbon discrimination time-series was compared with paleorainfall estimates developed from stable oxygen-isotope speleothems in Soreq cave in Israel (Bar-Matthews et al., 1998, 2003). Destruction and occupation layers from Minoan and Mycenean sites were organized into a database after a review of literature (Tables 1 and 2, Supplementary Material) (Andreadaki-Vlazaki, 2010; Andreou, 2010; Cavanagh, 2010; Colombaroli et al., 2009; Dakouri-Hild, 2010a,, 2010b; Davis, 2010; Driessen, 2010; French, 2010; Heath Wiencke, 2010; La Rosa, 2010a; La Rosa, 2010b; Laffineur, 2010; MacDonald, 2010; MacGillivray and Sackett, 2010; Maran, 2010; Platon, 2010; Shaw and Shaw, 2010; Voutsaki, 2010). Occupation layers were added for each time period from the Early Helladic 1 to the Late Helladic IIIC and subtracted by destruction and abandonment layers.

Broader records of Holocene climate were included to show changes in the Northern Hemisphere contemporaneous with the LBA Collapse. Northern Hemisphere temperature reconstructions derived from the Greenland Ice Sheet Project (GISP2) (Alley, 2004) and solar irradiance data derived from cosmogenic radionuclide ^{10}Be (Steinhilber et al., 2009). Reconstructed temperature and temperature anomalies record global climate conditions, solar irradiance assesses the potential for solar forcing of climate. Solar activity has been found to correlate with SST in the Northern Hemisphere (Jiang et al., 2005), and with wind can contribute to broad changes in SST.

4.2. *Marine records*

Alkenone SSTs were reconstructed from sediment cores in the Ionian Sea (Emeis et al., 2000), Aegean Sea (Rohling et al., 2002), and Adriatic Sea (Sangiorni et al., 2003). The ratio of warm/cold species dinocysts in the Adriatic (Sangiorni et al., 2003), and formanifera in the Aegean (Rohling et al., 2002) provide an additional indicator for relative changes in SST. Dating for sediment core LC-21 in the Aegean reveals an age discrepancy of 330 years for ash from the Santorini eruption (Rohling et al., 2002), in the present study all dates falling within the past 5000 years were corrected (−330 years) to match this historical event dated to 1623–1627 BCE based on SO$_4^{2-}$ residuals above 25 ppb in the GISP2 core (Zielinski et al., 1994).

4.3. *Data analysis*

Analysis of paleoclimate proxies and changes in human occupation was performed using Bayesian change-point analysis. The Barry and Hartigan (1993) algorithm was employed, with defaults following the recommendations of Erdman and Emerson (2007), including 10,000 burn ins, and 10,000 Markov chain Monte Carlo resampling events. This procedure assesses the chance of a significant change-point through the use of partitions. Each partition mean was denoted as μ_{ij}, where μ represents the mean of the block between points $i + 1$ and j. Each data observation is held to be independent $N(\mu_i,\sigma^2)$ with a prior distribution of $N(\mu_0, \sigma_0^2/(j-i))$. For each calculated partition mean, a probability of a change point is assessed through the sum of squares inside and between the partitions. Over multiple iterations, the means are averaged to produce a posterior mean with a posterior probability for a change-point. The bcp package developed by Erdman and Emerson (2007) for R was used to run Bayesian change-point models. This analysis helps assess the significance of changes that are found during the critical time period in the Late Bronze Age/Early Iron Age. Specifically, a high posterior probability will indicate a significant long-term change in a paleoclimatic record. An event with a low posterior probability does not necessarily mean it is not-significant, but it may indicate that the partition contained an isolated event, rather than a long-term climatic change. The posterior probability can be used to more precisely time changes in the paleoclimatic records.

All statistics and charts were generated using the open-source statistical program R, source code is included in supplementary materials. Compilation of figures and charts took place using Adobe Photoshop CS5.

5. Results

Discrimination rates for ^{13}C calculated from stable carbon isotope data in lake pollen records decline with paleorainfall reconstructed from the stable oxygen-isotope record in Soreq cave. Ionian SST values indicate a decline of 3–4 °C during the time period of the hypothesized arid period following the LBA collapse, reaching its coldest point in the Holocene (Emeis et al., 2000). A similar, though less severe, decline of 2–3 °C occurred during the Medieval Warm Period (1000–1200 CE; Lamb, 1982). However, it is difficult to attribute specific climatic events to the low-resolution Ionian SST record without similar records being available for the same time period. The Adriatic SST data shows a more moderate cooling of 1–2 °C at the time of the LBA collapse and a 24% reduction in warm-species dinocysts (Sangiorni et al., 2003). Foraminiferal records from the Aegean Sea indicate a 25% reduction in warm-species foraminifera. No change in SST is observed in data from the Levantine Basin in site ODP-967, though the age model for ODP-967 has been the subject of recent revision (Emeis, personal comm.). Declines in sea surface temperatures would result in less evaporation, which would reduce the exchange of water vapor from marine to atmospheric reservoirs. Less water would in turn precipitate during storm events.

Change-point posterior probabilities indicate that the warm-species foraminiferal/dinocyst declines in the LBA are among the most significant in their respective Holocene records (Table 1). Posterior probabilities document long-lasting declines in warm-species dinocysts, warm-species formanifera, sea surface temperature, and paleorainfall during the LBA/EIA transition. The highest posterior probabilities occur with changes dated to the period between 1694 and 1197 BCE, these are associated with dinocyst and formanifera records in the Adriatic and Aegean seas, respectively. Site abandonments in the Aegean and Crete occur in a more narrow timeframe between 1315 and 1050 BCE. Ionian SST drops at a later date, between 1011 and 715 BCE.

Northern Hemisphere temperatures drop over 2 °C between 1350 and 1124 BCE (Fig. 4). Cold conditions continue until 400 BCE. Solar irradiance data suggests at least two drops in solar irradiance comparable to the Maunder Minimum occurred during the 'Greek Dark Ages', the period of coldest temperatures during the Little Ice Age (Eddy, 1976).

6. Discussion

Paleoclimatic inference from low-resolution records is difficult. These difficulties are compounded for marine records where carbon reservoir effects can complicate radiocarbon dates, as noted by Rohling et al. (2002). Bayesian change-point analysis was employed to provide a statement of significance regarding the changes observed in paleoclimate records. High posterior probabilities are associated with the decline of warm-species dinocysts/foraminifera in the Adriatic and Aegean seas by 1197 BCE. Evidence for aridity through terrestrial paleoclimate proxies follows by 1050 BCE, though with low posterior probabilities. The Ionian SST record indicates a drop in temperature after 1011 BCE (Fig. 3), after the

Table 1
Posterior probabilities for change-points in Palatial Center occupation and Paleoclimate Proxies. Posterior probability refers to the degree of change relative to most of the Holocene record (2000 CE–8000 BCE), e.g. the collapse in Mainland Greece Palatial Centers is a much stronger deviation than the same events in Crete as Crete experienced earlier destructions related to the conquest by Mainland Greece and the Santorni eruption. The decline in Ionian SST and both Adriatic and Aegean warm-species dinocysts and formanifera were the largest changes in those records throughout the Holocene. Time periods with high posterior probabilities may contain a significant change.

Record	Date	Change	Posterior probability
Cretan Occupation	1315–1190 BCE	Site Destructions and Abandonments	24.49%
Mainland Greece Occupation	1315–1190 BCE	Site Destructions and Abandonments	90.37%
Paleorainfall in Soreq Cave	1050–650 BCE	Drop in paleorainfall (~100 mm)	9.82%
^{13}C Discrimination in Lake Voulkaria	1466–875 BCE	Drop in ^{13}C discrimination/ drought response (8‰)	1.08%
Ionian SST	1011–715 BCE	Drop in sea surface alkenone temperature (3–4 °C)	18.14%
Adriatic SST	1326–1135 BCE	Drop in sea surface alkenone temperature (1–2 °C)	2.02%
Adriatic Dinocysts	1450–1250 BCE	Decline in warm-species dinocysts (24%)	75.80%
Aegean Formanifera	1694–1197 BCE	Decline in warm-species formanifera (25%)	99.98%

beginning of the Greek Dark Ages. While not all records align in a straightforward manner, most are consistent with the interpretation of cooler, more arid conditions during the Greek Dark Ages. Furthermore, terrestrial records identify a known climatic event, the Roman Warm Period (Orland et al., 2009), to 1CE/1BCE (Fig. 2). It is important to remember that the paleoclimate proxies that indicate this period of aridity are low-resolution records, adding uncertainty to their interpretation.

Multiple climate indices from across Europe, Asia, and Africa indicate arid conditions in the last millennium BCE as well. The period has been broadly characterized as the “Iron Age Cold Epoch” by Van Geel et al. (1996). Low lake levels suggest warm, arid conditions in Italy (Dragoni, 1998; Sadori and Narcisi, 2001), the Swiss Alps (Jus, 1982) and France (Digerfeldt et al., 1997), with the low levels occurring from 1150 to 850 BCE. Lake sediments in the Swiss Plateau and timberline fluctuations in the Swiss Alps suggest a warm period from 1250 to 650 BCE (Haas et al., 1997). Lowering lake levels in the peri-Adriatic region (Magny et al., 2006, 2007; Drescher-Schneider et al., 2007) and an expansion of Quercus ilex (Colombaroli et al., 2009) suggest a shift to arid conditions after 1050 BCE in the Balkans. In Africa low lake levels occurred in Lake Turkana from 1050 to 150 BCE (Owen et al., 1982). The Sahara in Mali appears to stabilize as a severe arid climate around 1050 BCE (Petit-Marie, 1987). The dry conditions of the Chad Basin start around 1050 BCE after an earlier wet period. In East Asia, cold and arid conditions occurred at this time. A cold, arid period occurred on the Tibetan Plateau from 1050 to 550 BCE (Fu-Bau and Fan, 1987), while heightened aridity is identified in the Loess Plateau from 1150 to 250 BCE (Huang et al., 2000). Finné et al. (2011), in a review of 18 paleoclimate proxies, also identify cold and arid conditions in the Eastern Mediterranean at the close of the LBA.

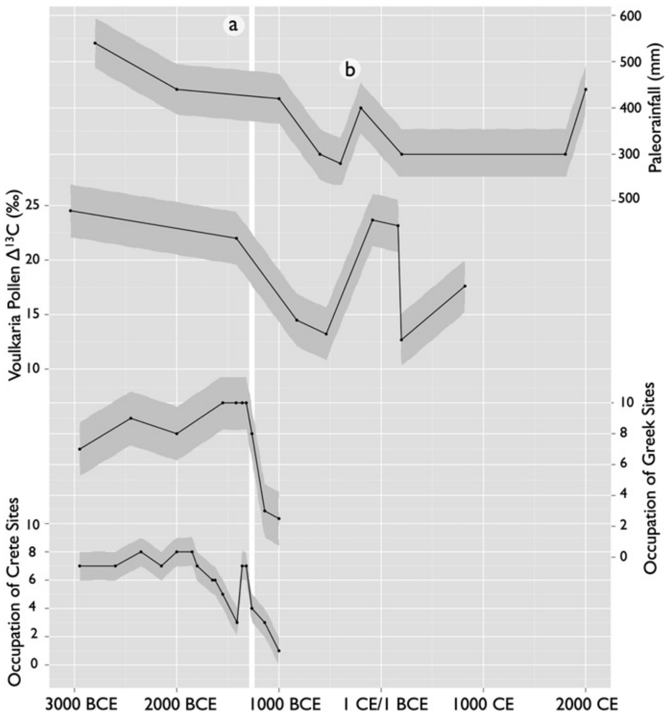

Fig. 2. Paleo annual rainfall reconstructed from oxygen-isotope speleothem data (top; Bar-Matthews et al., 2003) and ^{13}C discrimination calculated from pollen radiocarbon dates (second line; Jahns, 2005). Both records indicate a drop in precipitation beginning near the LBA collapse (a) and continuing through the “Greek Dark Ages”. Both records also indicate a climatic recovery during the Roman Warm Period (b). Occupation of Palatial centers in Greece (third line) and Crete (last line) show a sharp drop near the beginning of the hypothesized arid period. Dark shading around lines represents 95% confidence bands. The LBA collapse, extends from (a) to the final disappearance of recognizable Mycenaean culture before 1000 BCE.

Cooler SSTs have been associated with reduced temperatures in the spring (Sangiorni et al., 2003) and winter (Rohling et al., 2002). Rohling et al. (2002) have suggested that Aegean SSTs can be attributed to pressure differences resulting from cyclic atmospheric cooling events and northerly wind/polar air masses moving over the Mediterranean. However, SSTs can be influenced by factors other than atmospheric cooling. A similar decline in sea surface temperature occurs in the Northeast Atlantic during the Medieval Warm Period (Krawczyk et al., 2010). Warming of the SST’s occurred during the Little Ice Age in the same region. Krawczyk and colleagues suggest that warming around 1000 CE led to increased glacial melt, which resulted in an influx of cold freshwater that lowered SSTs. This created an anti-phase event, where warming ultimately results in a drop in SST. Recent work has shown that sea levels rose along the coast of North Carolina in the United States during the Medieval Warm Period due to glacial melt, and stabilized during the Little Ice Age (Kemp et al., 2011). Data from the Ionian Sea suggests that the Medieval Warm Period also resulted in a lower SST of 1–2 °C (Fig. 3: c), though this is evidenced by only a single data point, as it is a low-resolution record. While available evidence suggests that the LBA/EIA period was arid, it is not clear whether this was characterized by warmer or colder conditions.

Low Mediterranean evaporation rates would have had negative impacts on dryland agricultural systems in Mainland Greece and Crete. The long-lasting nature of these climatic changes would have put a severe stress on the ability to produce food for large populations. The collapse of LBA Palatial Civilization and the ensuing centuries of low population levels were possibly influenced by these changes in climate. Low sea surface temperatures and arid conditions let to a drop in precipitation across the Eastern Mediterranean, resulting in drops in agricultural productivity as hypothesized by Kaniewski et al. (2010).

The argument for a long-lasting change in climactic conditions is superficially similar to the drought argument proposed by Carpenter (1966). However Carpenter’s argument was for an event, not a broad centuries-long decline in conditions. The drought proposed by Carpenter (1966), Bryson et al. (1974), and Weiss (1982) was short, lasting no more than 5 years. Advocates for the drought hypothesis point to meteorological patterns in during the 1950’s drought as an indication of conditions around 1200 BCE; however droughts such as the 1950’s do not appear to be exceptionally rare in the instrumental record of precipitation in Mainland Greece (Grove and Rackham, 2003). A short-term, albeit severe, drought is an unlikely candidate for the widespread abandonment of Palatial Centers, a process that took decades at a minimum. Internal instability (Andronikos, 1954), population migrations (Desborough, 1964), and earthquakes (Nur and Cline, 2000) all likely played a significant role in site destructions. Whatever the cause of some or all site destructions, the broader question is why these centers were not rebuilt and reoccupied following catastrophic events. Occupants in Crete withstood both the Santorini eruption around 1620 BCE (Manning, 2010) and external invasion around 1460 BCE (Hallager, 2010), yet major Palatial centers were quickly rebuilt and reoccupied. The changes at the end of the LBA/EIA were far more pervasive and persistent – suggesting that long-term external processes underlie the synchronous cultural and economic decline.

The changes at the end of the Bronze Age could be better characterized as a ‘gear shift’ in Mediterranean climate. This shift in precipitation would not have been a crises event, but rather a continual stress put on human societies in the region for several generations. There was no one year where conditions became untenable, nor one straw that broke the back of the camel. Climate

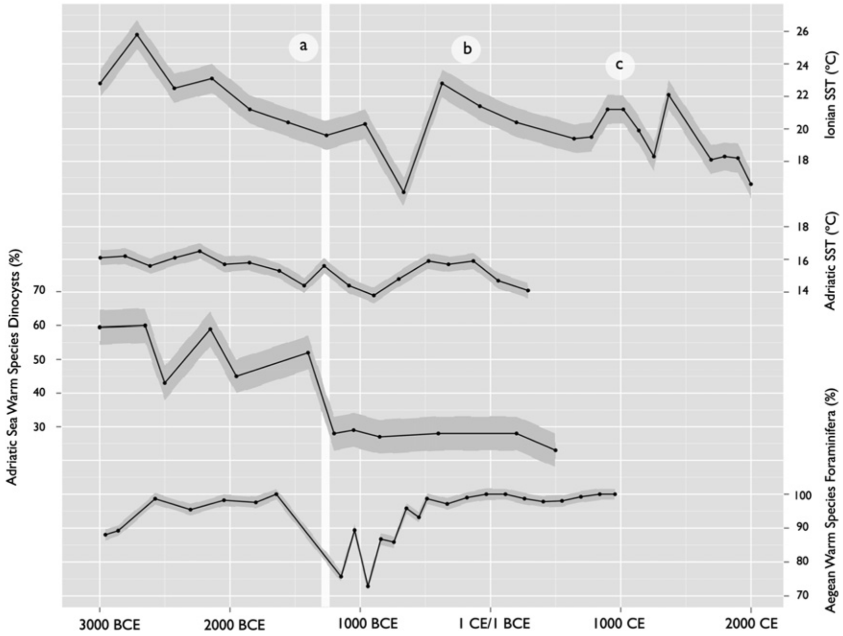

Fig. 3. Eastern Mediterranean sea surface temperatures (SST) as indicated by alkenone temperatures and warm-species formanifera. A drop of SST can indicate lower levels of evaporation, which in turn indicate less precipitation. The Ionian Sea (top line; Emeis et al., 2000) dropped by 4 °C following the LBA Collapse (a). Temperatures returned to their pre-LBA Collapse levels during the Roman Warm Period (b). A drop of 3 °C during the Medieval Warm Period (c) occurs as well. Adriatic SST (second line; Sangiorni et al., 2003) dropped 1–2 °C after the LBA Collapse (a), however a 25% reduction in Adriatic warm-species dinocysts (third line; Sangiorni et al., 2003) before the LBA Collapse (a) suggests cooling may have been rapid and severe. A similar decline in warm-species formanifera in the Aegean Sea (last line; Rohling et al., 2002) at the same time suggests significantly cooler waters as well. Dark shading around lines represents 95% confidence bands.

pressure began during the LBA, and didn't reach its nadir until the heart of the Greek Dark Ages. This change in average precipitation fits better with the economic and military interpretations of the decline in Mycenaean civilization. It provides a key external pressure for long-standing economic decline, and a motivation for population migrations such as that of the 'Sea People'. Climate-influenced drops in food production could have destabilized Aegean Palatial Centers, resulting in internal uprisings as proposed by Andronikos (1954). Such changes could have been analogous to rebellions that swept the Arab world in early 2011 that were caused by increasing food prices (Zurayk, 2011). As Palatial centers fell, migrations began across the Eastern Mediterranean, leading to further destabilization of the Late Bronze Age economy (Vermeule, 1960; Iakovides, 1986). With continued declines in dryland agricultural productivity and migration-influenced disruptions in trade, a point was reached where complex palatial center economies were untenable given the environmental and social conditions, thus resulting in a system's collapse. Larger population migrations led to military conflict, particularly the incursions of 'Sea Peoples' into Egypt and the Levant. In the Levant, urban centers

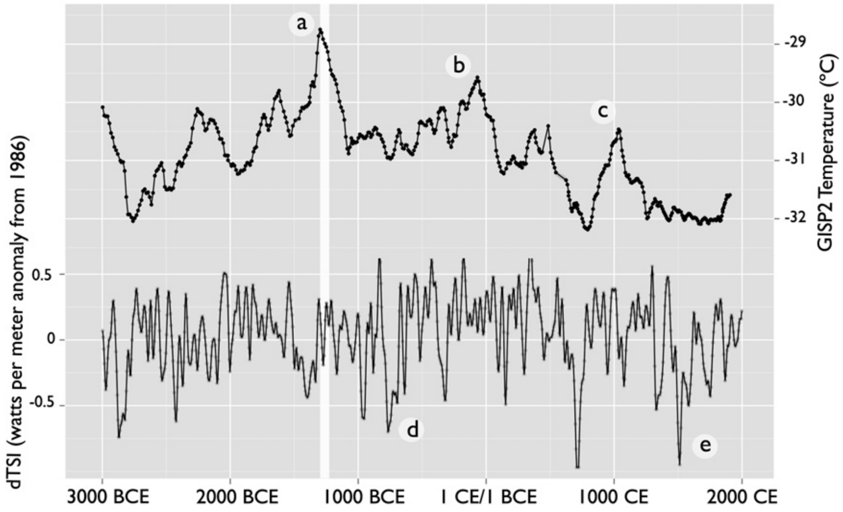

Fig. 4. Greenland Ice Sheet Project (GISP2) Temperature (top line; Alley, 2004) and a 20-point moving average of Solar Irradiance (bottom line; Steinhilber et al., 2009) for the past 5000 years. A large increase and sharp decrease in Northern Hemisphere temperatures occurred during the LBA Collapse (a). Similar (albeit smaller) temperature decreases terminated the Roman Warm Period (b) and Medieval Warm Period (c). Low solar irradiance, periods typified by low sunspot activity, are associated with cooler SSTs. Low solar irradiance occurred during the Greek Dark Ages (d), potentially contributing to continued low SSTs. This period of low solar irradiance is comparable to the more well known Maunder Minimum (e).

such as Hazor and Megiddo are destroyed by the end of the Bronze Age at 1150 BCE (Ussishkin, 1985). However, many urban centers are reoccupied after brief periods of abandonment, indicating that the events of the Levant may have been less severe than in Anatolia or Mainland Greece (Mazar, 1990). Nonetheless, Early Iron Age settlements had greater architectural affinities with pastoralist tents than Bronze Age Palatial Centers (Finkelstein, 1988). This suggests an increase in nomadism and a punctuated break from previous urban centers.

Importantly, the collapse of LBA Palatial Civilization and the following 'Greek Dark Ages' may have been linked by the same climatic changes in the region. The collapse of complex social institutions at the end of the Bronze Age was in part the consequence of declines in precipitation and its cascading effects through the economy. However, the peak of aridity is not reached until well into the Greek Dark Ages. At this time populations were much lower than they were during the Bronze Age, resulting in a paucity of archaeological data for occupation relative to other periods.

The recovery of populations in the region, marked by the rising importance of Athens as a trading center, does not appear to be climate related. Both precipitation and sea surface temperatures continue to be low, as evidenced by the available paleoclimate proxy records. The recovery of populations and the re-urbanization of Greece may have been related to innovations in agriculture, specifically the use of iron plowshares (White, 1984), and iron sickles (Hitti, 2004) beginning near 1000 BCE. While the decline of Bronze Age Palatial civilization may have been strongly influenced by climate, the recovery of urban society in Greece appears to be more dependent upon human innovation. An improvement in climate (The Roman Warm Period) occurred around 350 BCE, shortly before the expansion of Hellenistic civilization and subsequent cultural dominance of Greco-Roman culture for centuries. It is possible that an improvement in climate was an enabling factor for broader economic connections in the Mediterranean and Near East. A second deterioration in climatic conditions occurred in 150 CE, as indicated by data from Soreq Cave and Lake Voulkaria. Detailed analysis of speleothems in Soreq suggest that this climatic change was associated with increased arid conditions in the Eastern Mediterranean (Orland et al., 2009) and a drop in Dead Sea levels (Bookman et al., 2004).

While many of the climate proxies available for the region indicate colder Mediterranean SSTs and arid conditions, it is important to note that all of these records are low-resolution. It is difficult to directly identify a point in time when the climate grew more arid. However Bayesian change-point analysis suggests that the change occurred before 1250-1197 BCE based on the high posterior probabilities from dinocyst/formaniferal records. Arid conditions would have been felt afterward as the Eastern Mediterranean freshwater flux was reduced. In the context of Holocene climatic changes, that the changes observed at the end of the LBA are not of the same magnitude as larger events that receive attention in the literature. There larger climatic shifts, such as the Younger Dryas, Heinrich events, and the 4.2ka event, are well documented in the literature (Mayewski et al., 2004; Finné et al., 2011). The lowering of Mediterranean SSTs in the LBA is a much smaller event in magnitude. Nonetheless, it has profound impacts on human settlement and culture for centuries. These findings suggest that the magnitude of a climatic shift is not directly transferable to the magnitude of changes in human social organization. Complex societies can have similarly complex vulnerabilities that are sensitive to relatively minor changes in climate.

7. Conclusions

A decline in Mediterranean Sea surface temperatures (SSTs) before 1190 BCE decreased annual freshwater flux by lowering evaporation rates. Westerly winds took in less water vapor, resulting in declining precipitation. Land-based climate proxies, including reconstructed rainfall from Soreq Cave in Israel and ^{13}C discrimination recorded from pollen in Lake Voulkaria indicate unusually arid conditions following the drop in SSTs. LBA Palatial Centers, heavily dependent upon agricultural production to support more urban populations, became increasingly leveraged against a highly variable precipitation regime on a long-term decline. Such climatic pressures would have influenced social tensions, and eventually led to competition for limited resources. This climatic change could have influenced the systems collapse of complex society in the Eastern Mediterranean, as well as influence the population declines, urban abandonments, and long-distance migrations associated with the period. The ensuing centuries are associated with low archaeological resolution, population mobility, and a lack of urban centers. Conditions improve following the introduction of iron tools, and accelerate at the beginning of the Roman Warm Period at 350 BCE.

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Appendix. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jas.2012.01.029.

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