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HOLOCENE CLIMATE VARIABILITY IN THE EASTERN MEDITERRANEAN, AND THE END OF THE BRONZE AGE

Eelco J. Rohling, Angela Hayes, Paul A. Mayewski, and Michal Kucera

The Late Bronze Age/Early Iron Age transition in the eastern Mediterranean (about 1200–900 BCE) coincided with one of the current interglacial (Holocene) Rapid Climate Change events (RCC), as documented in about 50 globally distributed climate proxy records (Mayewski *et al.* 2004). That compilation study demonstrates that the RCC between 1500 and 500 BCE was characterised by glacier advances on a global scale (in Scandinavia, Central Asia, North America, and the Southern Hemisphere), similar to other RCCs in the intervals 4000–3000 and 2200–1800 BCE, and 800–1000 and 1400–1850 CE. It is evident, therefore, that the RCC at around the end of the Bronze Age was not unique, but part of a repeating pattern of global climate deteriorations during the Holocene.

The present contribution reviews previous studies to evaluate the severity of the impact of the Holocene RCCs in the eastern Mediterranean region with emphasis on the RCC of 1500–500 BCE. It also evaluates the constraints on the timing relationship between the end of the Bronze Age and expressions of the RCC of 1500–500 BCE in the eastern Mediterranean region.

Holocene RCCs and the eastern Mediterranean

Besides global glacier advances, the Holocene RCCs are also marked by distinct increases in the concentration of K^+ ions (*i.e.* [K^+]) in the GISP2 ice core from the Greenland summit (Fig. 1: O'Brien *et al.* 1995; Mayewski *et al.* 1997; Mayewski *et al.* 2004). Potassium transport to the Greenland ice sheet is strongly related to the late winter-spring intensity of the atmospheric high-pressure conditions over Siberia (Meeker and Mayewski 2002). Enhanced [K^+] within the RCCs therefore suggests an intensification of Eurasian winter conditions.

The Holocene RCCs are also characterized by peaks in the sea-salt [Na^+] series from the GISP2 ice core (Fig. 1.1). These sea-salt [Na^+] variations closely reflect the intensity of the Icelandic Low (Meeker and Mayewski 2002). An intensified (deeper) Icelandic Low causes intensification of onshore winds to Greenland, so that sea ice stays longer each season, and more persists from season to season. The inferred increase of North Atlantic sea-ice extent and duration during the Holocene RCCs is supported by concomitant increases in Holocene, most likely sea-ice transported, ice-rafted debris concentrations in North Atlantic sediments during the RCCs (Bond *et al.* 2001).

A key record for the identification of Holocene RCCs in the eastern Mediterranean region has been developed by investigation of marine microfossil assemblages in sediment core LC21 (Rohling *et al.* 2002b). LC21 was recovered from the SE Aegean Sea, on the boundary between the north-south extended Aegean Sea and the west-east extended Levantine Sea. This is a highly sensitive location for the recording of expansions and contractions of the cooler Aegean signature relative to the warmer Levantine signature.

Temperature changes in the region of sediment core LC21 have been deduced from changes in the assemblages of marine unicellular zooplankton microfossils (planktonic foraminifera Rohling *et al.* 2002b). These were grouped in species clusters according to affinities to warmer or cooler conditions, yielding a relative record of warming and cooling. Based on mapping of the same assemblages in core tops from the Aegean Sea, the relative changes were roughly calibrated to quantitative estimates of sea surface temperature change. This suggested that the RCCs were associated with temperature drops of the order of 2–3°C in the SE Aegean region, notably in winter. We corroborate this initial estimate by similar values from statistically more robust calibrations of the faunal changes using an Artificial

Neural Network approach (Fig. 1.1: for method, see Hayes *et al.* 2005). In central Aegean Sea core SL-11 (Casford *et al.* 2002; Casford *et al.* 2003), the ANN method suggests a magnitude of cooling of about 2.5°C for the Holocene RCCs (unpublished data). This may suggest that the impact of cooling was stronger in more northern sites, and somewhat weaker further to the south, which would agree with the inferred cause of the cooling events in the Aegean Sea (northerly outbreaks of cold air – see below).

The approximate 2°C magnitude of the Holocene RCCs in the Aegean compares well with the magnitude of contemporaneous cooling events in the western Mediterranean, which were quantified with organic geochemical techniques (Cacho *et al.* 2001). Oxygen isotope analyses from speleothems in southwest Romania (Poleva Cave) also provide evidence of climatic cooling within this time period. In that record, the oxygen isotope record is used as a relative temperature proxy, and the magnitude of the decrease was not quantified. However, the observed shift of about 1.5‰ in the isotope data implies a significant temperature decrease in the period between 1500 and 500 BCE (Constantin *et al.* 2007). Another speleothem record, from Spannagel Cave in the central Alps, also shows a marked interval of relatively heavy oxygen isotope ratios (about 1500–800 BCE), which starts with a shift that implies around 3°C winter cooling (Mangini *et al.* 2007). The temporal structure of the Spannagel Cave record closely resembles that of records of North Atlantic hydrographic/sea-ice variations, as obtained from ice-rafted debris counts in marine sediment cores (Bond *et al.* 2001) and supported by the GISP2 ice-core [Na^+] series (Fig. 1.1). The combined information demonstrates a significant correlation between terrestrial and marine palaeoclimate records at this time, with an emphasis on winter-time perturbations.

The cooling events in the Aegean Sea have been ascribed to intensification and frequency increase of wintertime northerly outbreaks of cold polar and continental air over the basin, relative to the present (Rohling *et al.* 2002b). Such outbreaks still occur today (for a summary and data of such an event in the year 2001, see Casford *et al.* 2003). These outbreaks are a consequence of the Mediterranean's latitudinal position and its mountainous northerly margin, which exert an important control on circulation and

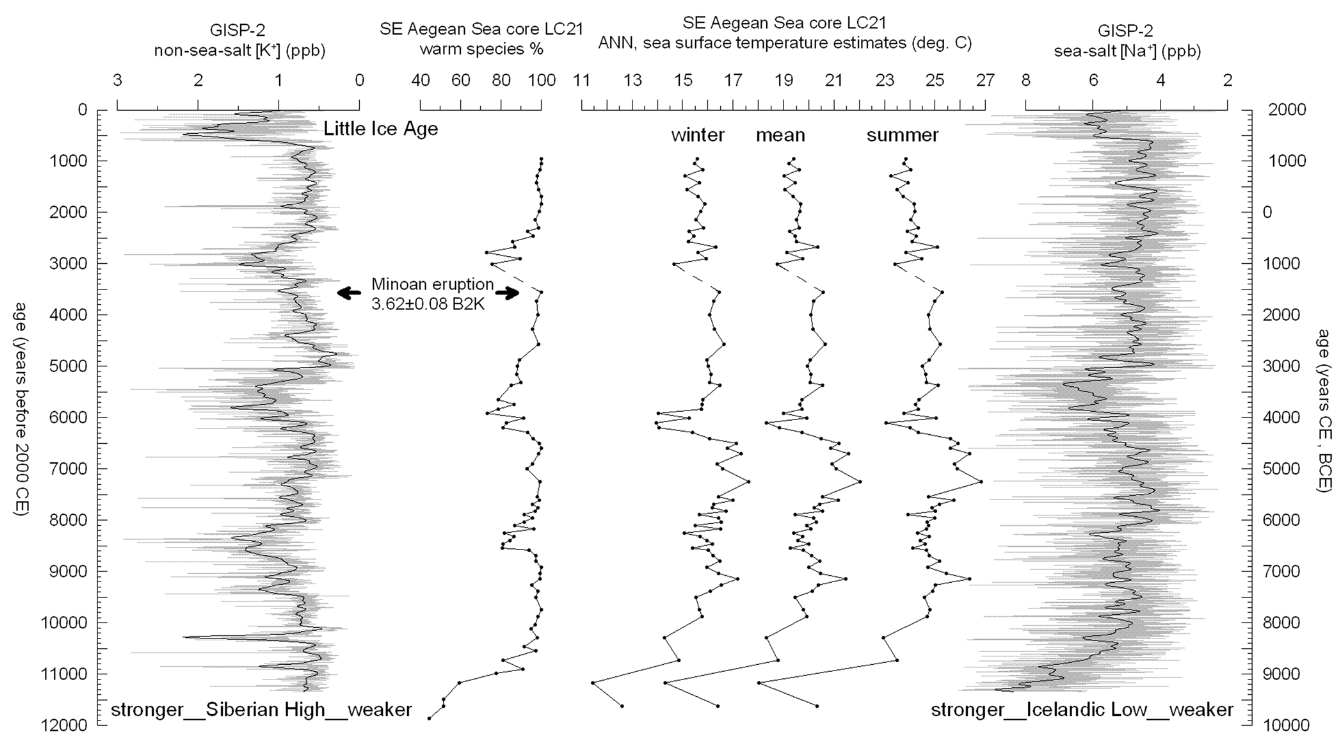

Fig. 1.1: Compilation of the Holocene non-sea-salt [K^+] and sea-salt [Na^+] series for the GISP2 ice core from Greenland (O'Brien et al. *1995; Mayewski* et al. *1997), with 200-year bandpass filters, along with the sea surface reconstructions for the SE Aegean Sea from planktonic foraminiferal abundance data for sediment core LC21. The qualitative warm species percentage record is the same as that shown in Rohling* et al. *(2002b). An artificial neural network (ANN) technique is used to transform the faunal abundance data into records of winter, summer, and annual mean sea surface temperature. The technique and its core-top calibration set are fully explained in Hayes* et al. *(2005). Note that the records are presented on the left-hand side versus age in years Before 2000 CE (B2K), which is the conventionally used ice-core reference datum, as well as (right-hand side) versus age in years CE/BCE (as used throughout this volume). The age of the Minoan eruption is indicated after Bruins and Van Der Plicht (1996) and Kuniholm* et al. *(1996)*

water-mass transformations in the Mediterranean Sea. Contemporaneous cooling events have been found in the Adriatic Sea and in the western Mediterranean (Rohling *et al.* 1997; Cacho *et al.* 1999; Cacho *et al.* 2000; Cacho *et al.* 2001; Casford *et al.* 2001; Rohling *et al.* 2002a; Frigola *et al.* 2007). To understand the relationship between the frequency and intensity of wintertime northerly outbreaks over the Mediterranean and the climatic patterns inferred from proxy records from the wider northern hemisphere (particularly the Greenland ice sheet), it is important to first consider the main drivers behind the general climatic conditions over the region.

During summer, climatic conditions over the Levantine Sea (the eastern sector of the eastern Mediterranean) are dominated by displacement of the North African subtropical high-pressure conditions to the north, causing widespread drought. The Aegean Sea then comes under the influence of northerly winds ('Etesians'), caused by extension of the deep monsoon low-pressure system of northwest India over the Iranian highlands and Anatolia. Although this semi-permanent extension of the monsoon low causes local depression formation around Cyprus and the Middle East, dry summer conditions prevail due to descent in the upper troposphere that is related to the intense Asian summer monsoon (Rodwell and Hoskins 1996; Trigo *et al.* 1999).

During winter, the North African subtropical conditions are displaced southward, and polar/continental conditions expand southward from the north. Low surface-pressure conditions over the central to eastern Mediterranean develop as a consequence of the high sea-surface temperatures relative to the surrounding land masses, fuelled by the high thermal capacity of the basin's water masses (Lolis *et al.* 2002). Interactions between this Mediterranean Low and north-eastward extension of the Azores High (over Iberia, France, and southern Britain), or westward ridging of the Siberian High towards northwest Europe and southern Scandinavia (Maheras *et al.* 1999; Lolis *et al.* 2002), drive intense northerly flows of cold and dry air masses towards the Mediterranean basin. These airflows are channelled (concentrated) through valleys in the mountainous topography of the northern Mediterranean margin. Channelling of polar and continental airflows through the lower Rhone Valley towards the Gulf of Lions gives rise to the 'Mistral', and similar flows towards the Adriatic and Aegean Seas cause the 'Bora' and 'Vardar'. These wintertime outbursts of polar and continental air cause intense evaporation and associated cooling of the sea surface (*e.g.* Leaman and Schott 1991; Saaroni *et al.* 1996; Poulos *et al.* 1997; Maheras *et al.* 1999; Casford *et al.* 2003 and the references therein).

As stated above, the enhanced potassium accumulation in the Greenland ice sheet during Holocene RCCs suggests an intensified late winter-early spring Siberian High. Given that expansion and westward ridging of the Siberian High is an important processes controlling northerly outbreaks over the Mediterranean (Maheras *et al.* 1999; Lolis *et al.* 2002), we infer that the enhanced Siberian High intensity during RCCs led to an increase in the frequency and intensity of northerly air outbursts over the Mediterranean (notably the Aegean). This would offer a realistic mechanism to explain the observed episodes of about 2°C winter sea surface cooling (up to ~3°C further to the north).

Timing and extent

If, as argued, the enhanced Siberian High intensity at times of RCCs caused an increase in the frequency and intensity of northerly air outbursts over the Mediterranean (notably the Aegean), then it would follow that the Aegean cooling events were in phase with non-sea-salt [K^+] maxima in Greenland. Within the constraints of the independent dating techniques for the Aegean sediment core (radiocarbon) and Greenland ice core (layer counting), this expectation was found to be valid for the RCC centred on about 6400 BCE, but for the younger RCCs this initial comparison appeared to suggest an older age for the RCCs in the Aegean region than in Greenland (Rohling *et al.* 2002b).

The apparent radiocarbon-based age 'offset' for the RCC of interest in Aegean Sea core LC21 could be evaluated using the presence in LC21 of a 10-cm thick ash-layer from the Minoan eruption of Santorini, which has been accurately dated at 1620 ± 80 BCE (Bruins and Van Der Plicht 1996; Kuniholm *et al.* 1996). The RCC in core LC21 followed sharply after the Minoan eruption. This comparison demonstrated that radiocarbon ages in the younger part of core LC21 were somehow biased towards 'too old' values by about a few centuries, and that the RCC actually started around 1500 BCE. This confirms that it is the temporal equivalent of cooling event TC2 (Cacho *et al.* 2001) and M3 (Frigola *et al.* 2007) in the western Mediterranean and, indeed, of the globally recognised RCC of 1500 to 500 BCE (Bond *et al.* 2001; Mayewski *et al.* 2004; Constantin *et al.* 2007; Mangini *et al.* 2007), which brackets the end of the Bronze Age and the Early Iron Age (about 1200–900 BCE). In Fig. 1.1, the chronology of the LC21 record has been adjusted to account for the correct age of the Minoan eruption (for details, see Rohling *et al.* 2002b).

The onset of the RCC shortly after the Minoan eruption is coincidental, and should not be interpreted to imply causality. David Pyle (1997) argued that an eruption similar to the Minoan eruption might cause a relatively cool period of only a couple of years, and it would be expected to be much more pronounced in proximal sites than in far-field sites. Hence, the multi-century duration and wide-spread (global) appearance of the RCC of 1500–500 BCE would not be consistent with the magnitude of the eruption, nor with the expected distribution pattern of any far-field impacts.

Also, other RCCs have been recognised within the Holocene without associations with major volcanic events (Mayewski *et al.* 2004). As yet, there is no comprehensive theory to explain the quasi-periodic recurrence of RCCs during the Holocene. The repeated pattern of Holocene RCCs appears to be truly global in extent, however, and comparisons with records of cosmogenic isotope (*e.g.* ^{14}C, ^{10}Be) production suggest that a relationship with small reductions in solar output should be considered (*e.g.* Bond *et al.* 2001; Mayewski *et al.* 2004, Maasch *et al.* 2005).

Globally, the RCC of 1500–500 BCE displays a distinct 'cool poles, dry tropics' configuration (Mayewski *et al.* 2004), and this character is obvious also in the eastern Mediterranean domain. A study of clay mineral ratios in SE Aegean sediment core SL123 – which is well dated and includes a clear Minoan ash layer – indicates a relatively high Nile River flow regime from 2200 to 1800 BCE, followed by a sharp decline that culminated in an arid episode from about 1600 BCE (at which level the Minoan ash layer anchors the absolute chronology) until about 800 BCE (Ehrman *et al.* 2007). The timing of the inferred 1600–800 BCE low Nile-flow period in core SL123 (Ehrman *et al.* 2007) agrees rather closely with that of the 1500–500 BCE northerly cold spell recognised in core LC21 (Rohling *et al.* 2002b, and Fig. 1.1). At the base of the interval, the chronologies of cores LC21 and SL123 are firmly anchored relative to one another (and Greenland) by the Minoan ash layer.

The onset of the northerly cold spell / low Nile flooding episode around 1600 to 1500 BCE coincides with a general shift to hyperaridity around 1500 BCE in the Sahara, which marks a culmination in the stepwise decline in moisture availability over that region since about 3500 BCE (Hassan 2002). In the Near East, stable isotope data from caves in Israel suggest a general aridification trend from 2500 to 500 BCE, with an especially arid culmination between 1000 and 500 BCE. During this arid culmination, estimated annual rainfall amounts over Israel may have reached only about 60% of modern values (Bar-Matthews *et al.* 2003).

Impacts

Relative to atmosphere, seawater holds an enormous amount of heat, so that a cooling of 2–3°C throughout the Aegean winter mixed layer (150 or more metres deep) would require a significant atmospheric forcing. Consequently, the impacts on land should be expected to have been much sharper and more pronounced, and to potentially consist of highly variable conditions with considerable extremes (which get 'smoothed out' by the long time-integration in the sea).

Today, occasional northerly outbreaks, with individual event durations of a week to several weeks, cause widespread sharp frosts and aridity (upwind of the water), and snowfall (downwind from the water) around the Aegean shores. During periods when northerly winter outbreaks were more intense and/or frequent – sufficient to cause a sea surface temperature drop of about 2°C – significantly intensified winter frosts and aridity might be expected upwind of the water, notably along the northern and northeastern sectors of the Aegean coast, with milder frosts and snowfalls downwind of the water. To evaluate whether these projected consequences were sufficiently severe during the event of 1500–500 BCE to affect the agricultural quality of the land and consequent food production, highly resolved continental records are needed that can be unambiguously correlated to the marine records.

Outside the Aegean Sea, the northerly cooling influences seem to have been dampened (probably by the vast heat reservoir of the open Levantine Sea) so as to become undetectable. However, records do reveal similarly dated events of enhanced aridity around the southern Levantine margin and in the Near East. From around 1600 BCE there was a period of substantially reduced Nile flooding that lasted about 800 years. In the critical setting of the Nile valley, reduced flooding would likely have affected the agricultural capacity, while the definitive step to hyperaridity in the wider Sahara around 1500 BCE would have finally rendered that environment incapable of any substantial food production. In the Near East, there was a sharply defined arid episode between 1000 and 500 BCE, which would appear to have been severe enough to influence the agricultural capacity of that region.

The question remains whether the listed changes in the Aegeo-Levantine climate would have been severe enough to have a lasting impact on societal structures. To answer that question, more highly resolved records will be needed from around the region, with carefully established correlations between sites (*e.g.* on the basis of volcanic ashes within the various sequences). In addition, any impacts of regional climate change would need to be considered within an appropriate context of potential adaptability to adverse conditions by means of trade within existing (seafaring) networks.