Charcoals from the Past: Cultural and Palaeoenvironmental Implications

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Solar influence on Holocene fire history

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Abstract: It has been suggested that climates during the Holocene have varied on timescales of about 1500 years, forced by oscillations of a solar cycle. These climatic changes have been implicated as the cause of changes in geological records from, mostly, marine sediments. If there were such changes, and if they were of great enough amplitude to force changes in marine sedimentation, it would be reasonable to expect to see some changes in terrestrial environments. One record that is available across most terrestrial environments is the record of charcoal that results from the burning of vegetation. As burning might be expected to be more frequent under hot dry climates, this might react well to the climatic changes expected for maxima in the solar cycle, and thus provide a contrast to the reverse behaviour during solar minima. We examined eight records of microscopic charcoal from Europe and Australia, from temperate and more arid environments, using a range of statistical techniques to look for behaviour that might be caused by oscillating climates. None of the tests was positive. However, we did identify a range of behaviours indicative of specific structure in burning patterns (they are not random in time or intensity). Apart from an influence in some sites of late Holocene anthropogenic buring, there also appears to be little regional correlation in burning patters. We suggest that, for these eight records at least, burning events appear to be, on the whole, site-specific.

Introduction

There is increasing acceptance amongst palaeoclimatologists that a millennial-scale climatic cycle, operating independently of the glacial-interglacial climate state, is apparent in the Holocene (Bond *et al.* 1997). A series of climatic shifts oscillating every 1470 ± 500 years is detected by various fossil proxies in marine and terrestrial sequences. Bond *et al.* (2001) have suggested that solar forcing is the main driving mechanism behind these climate changes. Broad teleconnective responses associated with these Bond cycles are suggested to have resulted in global climate changes including intervals of cooler climates in mid to high latitudes (Bond *et al.* 2001; Björck *et al.* 2005; Hu *et al.* 2003), reduced rainfall and aridification events in mid-latitudes and reduced monsoonal activity in low latitudes (Fleitmann *et al.* 2003; Wang *et al.* 2005). However the evidence for vegetation change associated with these Bond cycles is far from ubiquitous in time or space and identifying the influence of a millennial-scale climatic cycle on the Holocene vegetation dynamics is not straightforward (Heiri *et al.* 2004). Perceived changes may be region specific, time-transgressive (lags due to migration rates) or influenced by other abiotic and biotic factors.

A number of links have been made between Holocene biomass burning identified in sedimentary microfossil charcoal records and climate change (e.g. Carcaillet *et al.* 2002; Pierce *et al.* 2004; Whitlock 2004). However, no attempts have been made to directly examine the relationship between the solar forcing associated with Bond cycles and Holocene burning regimes. An obvious advantage of the charcoal record is that the response should not be time-transgressive. Variations may occur between regions, however, due to the flammability of the vegetation, regional climate etc. (Camill *et al.* 2003; Huber *et al.* 2004; Lynch *et al.* 2004) and on this basis it can be hypothesised that if there is a millennial-scale burning signature it might be more apparent in Mediterranean than north-west European records. Similarly in regions that have had significant prehistoric presence the record might become distorted — or this may even be a good method of distinguishing between human and natural fires in the Holocene.

In this study we aim to test statistically various hypotheses relating to millennial-scale climate oscillation and to examine the influence of solar variability on Holocene fire history using microfossil charcoal records from lake sedimentary sequences. Are there distinguishable burning patterns apparent in Holocene microfossil charcoal records? Are these related in time and frequency to the Bond cycles? Is there a latitudinal spread apparent from the Mediterranean region to northern Europe? Do these burning cy-

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cles become less distinguishable with the onset of anthropogenic burning? Failing to find a correlation between Bond cycles and burning cycles would enable us to reject a hypothesis that there is a causal relationship. Finding a correlation would leave that hypothesis open for further investigation.

All ages are given as calibrated years before present.

Methods

Charcoal data

Charcoal records from eight lake sedimentary sequences were examined in this study (Figure 1). All were from basins of <1 km in diameter and contained records spanning approximately 0-13,000 cal. yr BP. The geographical location of the sites was wide-ranging (Table 1) and included sequences from temperate, Mediterranean and tropical regions in the northern and southern hemisphere. With such a wide spatial distribution of sites it was envisaged that examination of the impact of Bond events in different vegetation biomes, and the global impact of solar forcing associated with Bond cycles, should be possible.

In all eight sedimentary records, the microscopic charcoal was extracted and counted alongside the fossil pollen record using the point-count method of Clark (1982). The size fraction measured was $<100\mu$ and represents a predominantly regional signal of burning. Charcoal particles contained within lake sedimentary sequences are a proxy that can have a regional, extralocal (nearby but not within the watershed) and local (within the watershed) spatial representation (Whitlock & Larsen 2001). However, previous studies (Whitlock & Millspaugh 1996; Gardner & Whitlock 2001; Clark *et al.* 1998; Ohlson & Tryterud 2000) have indicated that particle size in lake sedimentary sequences can be an important determinant of the spatial representation of the charcoal record (i.e. whether it represents local, extralocal or regional fires). These models predict that particles of a size fraction $>1000\mu$ tend to be released relatively close to the ground and deposited near to a fire (Clark & Patterson 1997). Consequently their presence in sedimentary sequences tends to represent local or extralocal fire events. In contrast, particles $<100\mu$ tend to be carried much higher up into the plume from the fire and as a result they can be carried aloft to great heights and transported long distances. The presence of these smaller particle sizes in a sedimentary record is therefore probably representative of a more regional signal of burning.

Diameter of the lake basin (or the size of the watershed relative to the basin) can also influence the proportion of charcoal received from a regional or local source (Birks 1997; Whitlock & Millspaugh 1996). Small lake basins ($<$1km) will receive a greater input from the environment immediately around the basin than a large lake. This is based on the assumption that a larger lake has a much greater surface area relative to the edge of the basin and will therefore receive more material from aerial transport. This will consequently magnify the input from the local environment in smaller basins relative to that from regional sources as demonstrated empirically in a number of studies (for a review see Whitlock & Larsen 2001). All basins in our study are $<$1km in diameter and therefore should detect both a local and regional signal.

Numerical analyses

The following statistical tests were applied to the data in order to determine whether there is a link between Bond cycles and patterns of burning apparent in microfossil charcoal records preserved in Holocene lake sedimentary sequences:

1. Skewness and kurtosis. These tests examine whether the fluctuations in the charcoal data reflect a normal distribution about the mean. A positive skewness value indicates too much data greater than the mean, and a positive kurtosis value indicates a curve too highly peaked relative to the normal distribution. A negative value indicates the converse.

2. Runs test. This test examines whether the fluctuations in the charcoal data show a distinctive structure. The test measures the frequency of samples that are consecutively higher (or lower) than the adjacent samples thus demonstrating a pattern of upward or downward trends in the sequence (which would not be present in random data). The test calculates a q statistic (where a q value greater than 0.05 would indicate a random pattern).

3. Correlation coefficients. Three different types of correlation coefficients (linear, Spearman's Rank and Kendall's) were used to test the relationship between charcoal values and time to determine whether there was a relationship between charcoal concentration and age. Negative correlations would indicate increasing amounts of charcoal with younger age.

4. Spectral analysis. This was carried out in order to determine any significant cyclicity in the burning records. A Lomb periodogram was applied, which is a type of spectral analysis intended to handle data that is unevenly distributed in time (Press *et al.* 1992).

Fig. 1. Results from the eight charcoal sequences (concentration values cm^2cm^{-3}) plotted against age [cal. yr BP]). Locations and references to sequences given in Table 1.

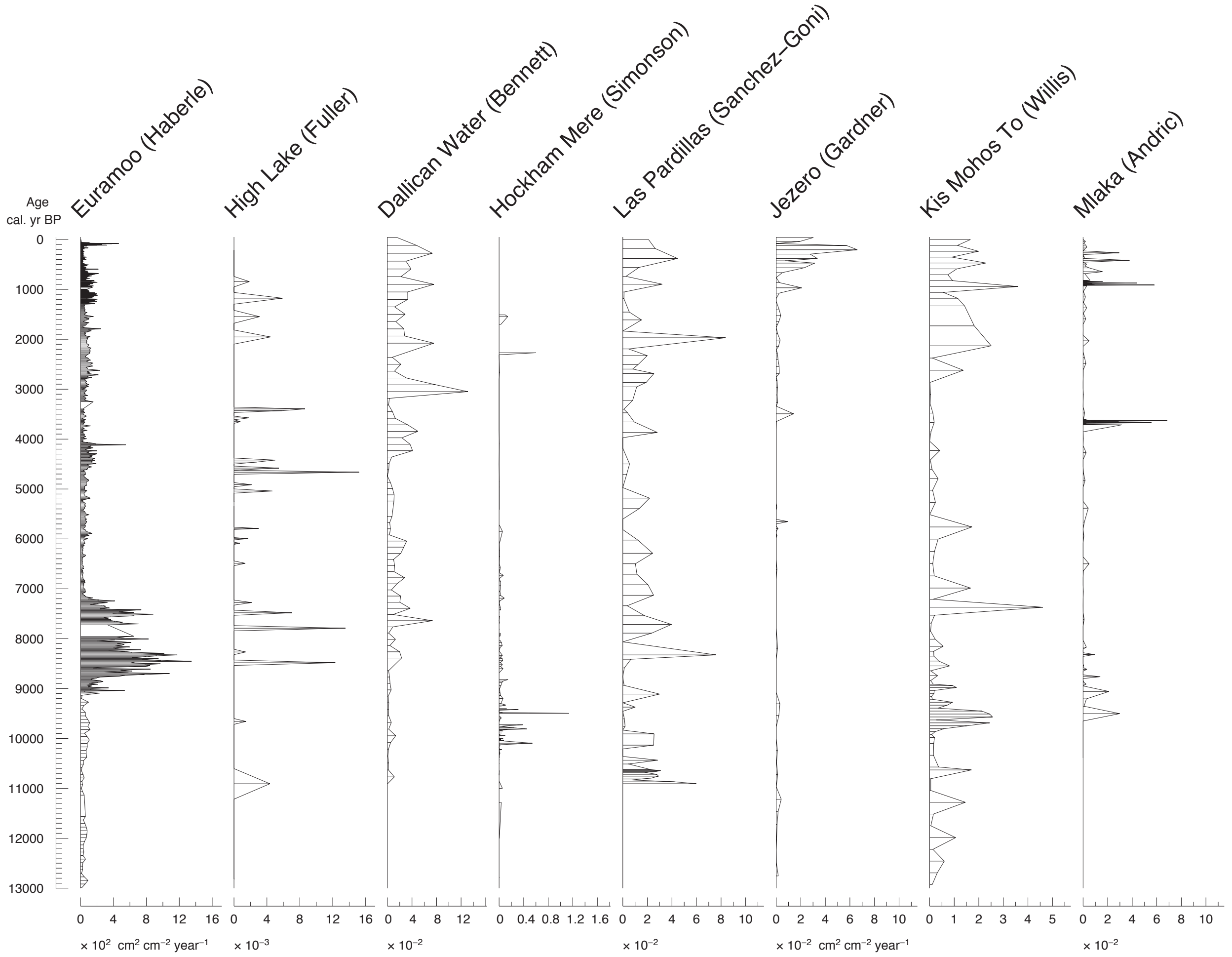


Table 1. Details of the eight sedimentary sequences used in this study.

Site	Location	Present day vegetation	Timespan of record (cal. years)	Authors
Dallican Water	Shetland, UK	Oceanic peatland	10000	Bennett *et al.* (1992)
Hockham Mere	Norfolk, UK	Temperate deciduous woodland	13000	Bennett *et al.* (1990)
Kis Mohos Tó	Hungary	Temperate deciduous woodland	13000	Willis *et al.* (1998)
Jezero	Slovenia	Temperate deciduous / Mediterranean	13000	A. Gardner & K.J. Willis, in prep.
Mlaka	Slovenia	Temperate deciduous	10000	Andrič & Willis (2003)
Pardillas	Spain	Mediterranean	11000	Sánchez Goñi & Hannon (1999)
High Lake	Ontario, Canada	Mixed deciduous coniferous forest	11000	Fuller (1997)
Euramoo	Queensland, Australia	Rainforest	13000	S.G. Haberle, unpub.

5. Chi-squared test. This was used to measure the association between changes in solar irradiance (maxima and minima as identified by Bond *et al.* 2001) and the charcoal records. For each record, significant charcoal peaks (that (a) exceeded a value greater then 3 standard deviations higher than the mean, and (b) exceeded the mean value) were identified. Each sequence was then divided into 65 x 200-year boxes and it was recorded for each site whether a peak occurred within a box. Also recorded was whether the Bond maxima or minima occurred in the same box. Each of the boxes for each sequence could then be classified as 'with charcoal' or 'without charcoal' and independently 'with maxima' or 'without maxima' and similarly for 'minima'. Contingency tables were then constructed to compare how many times the 200-year boxes with significant charcoal peaks coincided with Bond 'cycles' and how many times they did not. Both solar maxima and solar minima were tested.

Results

1. Results from the skewness and kurtosis tests (Table 2) indicate that for all sequences, the relationship is positive for both tests, indicating that (relative to the normal distribution) the charcoal data typically has a high proportion of values greater than the mean (skewed) and that the data is too highly peaked (leptokurtic).
2. In the runs test (Table 3) results indicate that all sites have q values less than 0.05 thus indicating that there is some trend in the datasets and that they are not simply the result of random changes over time.
3. Of the eight sequences only two (Dallican and Jezero) show significant correlations coefficients (Table 4). Both display negative correlations (increasing charcoal with younger age) that could be ascribed to human activity (Figure 1). There is no overall trend up or down the other six sequences (Figure 1).
4. Spectral analyses identify some level of cyclicity in all records, but only three sites (Euramoo, Jezero and Dallican) is there cyclicity sufficiently prominent to be considered significant (Figure 2). In all three cases, the significant cycles have a periodicity of about 10,000 years. It is probable that these are related to the overall trend along the sequence, also demonstrated by the correlation coefficients for Dallican and Jezero (Table 4). Overall, therefore, results from the spectral analysis suggest that none of the sequences display within-Holocene cyclicity.
5. The chi-squared tests (Table 5) indicated, with one exception, that there was no association between

Table 2. Results from the skewness and kurtosis tests indicating that in both tests there is a positive and significant relationship and that each sequence possesses a non-normal distribution.

Site	Mean	SD	Levels >3SD	Skewness	Kurtosis
Euramoo	80.8242	88.8443	Many	2.54*	8.20*
Pardillas	0.0157	0.0171	2	1.70*	3.69*
Kis Mohos Tó	0.7194	0.8952	2	1.83*	3.69*
Mlaka	0.0047	0.0177	1	3.51*	12.68*
Dallican	0.0197	0.0230	1	2.23*	6.15*
Hockham Mere	0.0439	0.1238	4	5.90*	41.88*
High Lake	0.0006	0.0021	5	4.50*	22.39*
Jezero	0.0039	0.0108	3	3.81*	15.68*

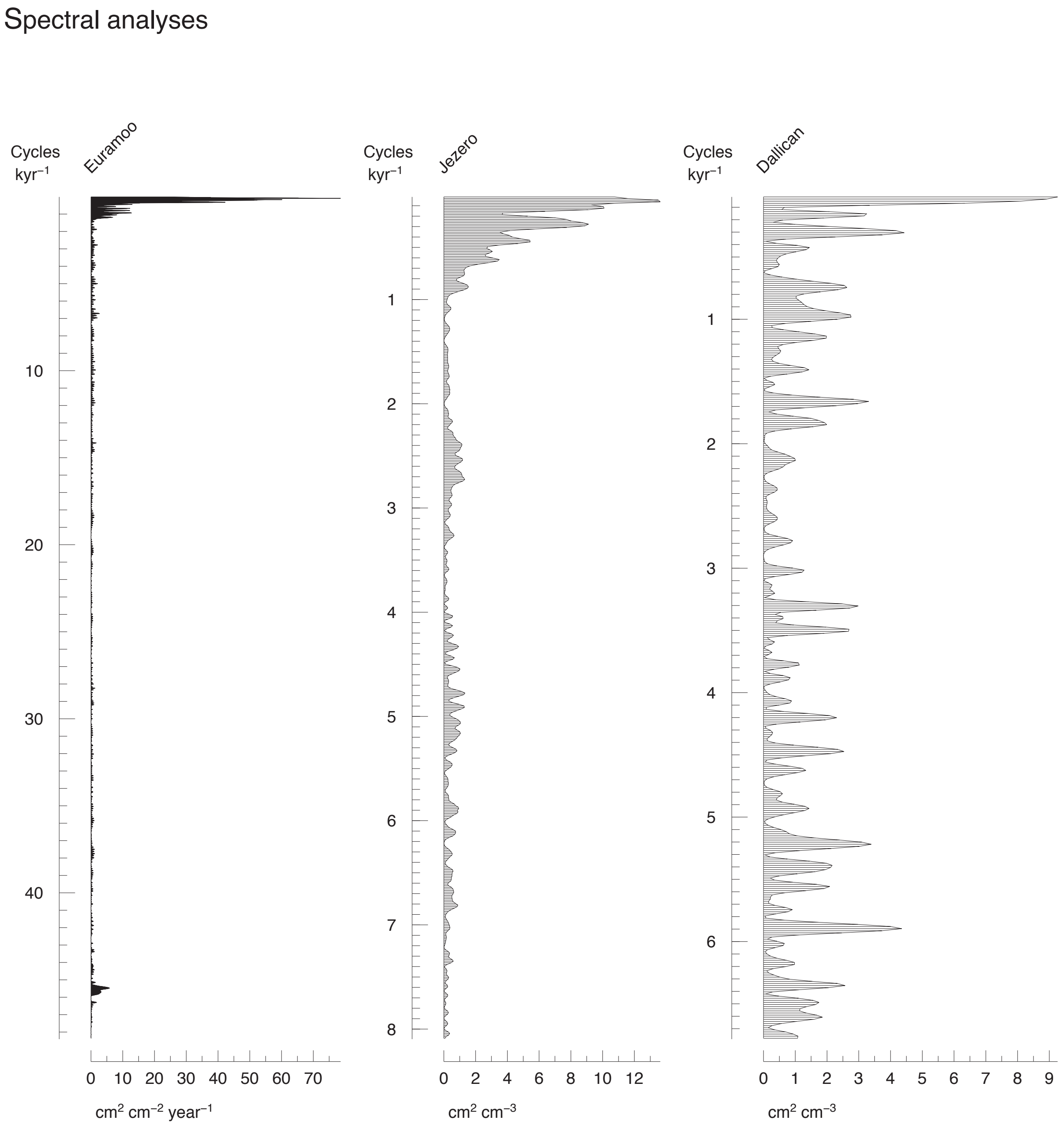
Table 3. Results from the runs test. All sites possess a q-value much less than 0.05 indicating some structure in these datasets and that they are not simply random changes over time.

Site	Runs q
Euramoo	6.92×10^{-4}
Pardillas	5.17×10^{-13}
Kis Mohos Tó	2.97×10^{-10}
Mlaka	1.24×10^{-8}
Dallican	1.91×10^{-11}
Hockham Mere	1.26×10^{-6}
High Lake	1.55×10^{-108}
Jezero	1.13×10^{-24}

Table 4. Results from the three correlation coefficient tests. Only two of the sites (Dallican and Jezero) have significant correlations, which can be ascribed to human activity in the later Holocene.

Site	Linear	Spearman's	Kendall's
Euramoo	0.1701	-0.0083	-0.0027
Pardillas	0.0704	0.1244	0.0656
Kis Mohos Tó	-0.2254	-0.1372	-0.0830
Mlaka	-0.1683	-0.2578	-0.2635
Dallican	-0.4765*	-0.6000*	-0.4232*
Hockham Mere	0.0012	0.0967	-0.0146
High Lake	-0.0480	0.6992*	-0.0762
Jezero	-0.4220*	-0.1718	-0.2958

Fig. 2. Results of spectral analyses from three sites, plotted as the amount of charcoal associated with each possible periodicity. 95% significance values are: Euramoo 10.1 $cm^2cm^{-3}yr^{-1}$, Jezero 8.3 cm^2cm^{-3}, and Dallican 8.1 cm^2cm^{-3}. Only peaks that exceed these values are significant.



Bond maxima/minima and peaks in the eight charcoal records. One of the Euramoo analyses (3SD charcoal peaks and solar maxima) is significant at the 95% level. Overall, therefore, these analyses provide no evidence for association between the Bond maxima/minima and charcoal peaks.

Discussion

Statistical examination of the eight microfossil charcoal records revealed that in all sequences there are distinguishable burning patterns apparent the Holocene; thus these burning 'events' are not part of a normal distribution nor are they random. In addition it would appear that in the majority of the sites (6 out of 8), the burning pattern was not merely reflecting increased fires with the onset of anthropogenic activity, but rather the occurrence of burning 'events' of comparable severity throughout the Holocene. These results in themselves are significant because they indicate that fire has had an important influence on the landscape throughout the Holocene and not just in the recent past. It also suggests that although increased burning linked to anthropogenic activity may be detected on local basis, and indeed had been clearly demonstrated in a number of other studies (e.g., Clark & Royall 1995), it cannot be assumed that there was an overall large-scale regional/continental signal of burning events in the later Holocene (see also Maxwell 2004).

The next question to be addressed, therefore, is whether these Holocene burning records indicate a temporal structure both within and between sequences. Examination for a cyclical pattern of burning within each sequence suggested that there are no such trends. It could be argued, however, that it is not entirely surprising that there is an absence of 1500-year burning patterns in the sequences since the timing of the Bond cycles are far from regular in time. Events of solar minima are recorded at approximately 11,100; 10,300; 9400; 8100; 5900; 4200; 2800; 1500 cal. yr BP which indicates a quasi rather than regular cycle. There is also the question of whether we should be looking for a correlation between burning and periods of solar minima (Bond cycles) or solar maxima? Intervals of solar minima have been identified through other proxies to aridification events, cooler temperatures and reduced monsoon activity (Bond *et al.* 2001; Björck *et al.* 2005; Hu *et al.* 2003; Fleitmann *et al.* 2003; Wang *et al.* 2005), all of which may well induce fires. But evidence from a number of other macro- and micro-fossil charcoal studies have suggested that drier climatic conditions, at least in mid-latitude regions, do not necessarily induce greater fire. Rather it has been demonstrated that that there is a closer correlation between warmer and more humid climatic conditions (and thus vegetation productivity) and burning (Camill *et al.* 2003; Lynch *et al.* 2004). The question therefore arises whether we should instead be examining intervals of solar maxima when presumably there were warmer, more humid conditions? One such interval, for example, is the Medieval Warm Period (approximately 1100-700 cal yr, BP) which has been suggested to be linked variations in solar activity (Andresen *et al.* 2005). Solar maxima occur at intervals of approximately 1̃1,000–10,500; 10,000; 8750; 7650; 5000; 3500 and 2400 cal. yr BP (Bond *et al.* 2001).

When intervals of solar minima and solar maxima are displayed on the eight charcoal/age plots (Figures 3 and 4), it is tempting to ascribe peaks that appear to co-incide with 'Bond minima' or 'maxima' to be related to this mechanism. However, it is those that do not co-incide which present more of a problem. In the published literature there are numerous examples where peaks apparent in temporal sequences at approximately the 'right age' to a known environmental/climate change are attributed to such, but those peaks that does not co-incide are either i) ignored, ii) attributed to errors in the age-depth model (thus arguing that lack of coherency is due to an incorrect age-depth), or iii) taken as evidence that a different mechanism is responsible for the structure in the record. This somewhat subjective approach to the interpretation of correlation (or lack of it) between data in temporal sequences is a problem that is not only true of charcoal records but all kinds of palaeo-proxy data.

In this study, a chi-squared test was therefore specifically set up in order to remove some of this subjectivity and to statistically test the association of Bond cycles with the charcoal records. The chi-squared test enabled us to statistically determine whether enough of the peaks in each charcoal sequence (within a 200-year time slot — thus allowing for a certain amount of error in the age-depth model) co-incided with either peaks in solar minima or solar maxima so that it was possible to say that there was less than 5% probability that the degree of associated could have arisen by chance. This was first tested with charcoal peaks greater than 3 standard deviations and then for all charcoal peaks greater than in the mean (Table 5). The latter test was run in order to ensure that all small fluctuations in charcoal concentration were included in the calculation and that the result was not being unduly influenced by variations in concentration. Results from both of these tests clearly indicated that there was no significant association between solar variability (maxima or minima) and the charcoal sequences (Table 5). Thus whilst occasionally a peak in a sequence may coincide with a minima or maxima in solar variability, this did not occur often enough in any one sequence to be statistically significant. Lack of sample resolution across the critical intervals concerned may explain some of this result in a few of the sequences (e.g. Kis Mohos Tó) but in other sequences (e.g. Euramoo, Dallican Water, High Lake and Hockham Mere) where samples were counted once every 20–50 years (Figure 1), there was

Fig. 3. The eight microfossil charcoal sequences with intervals of solar minima (taken from Bond *et al.* 2001) indicated.

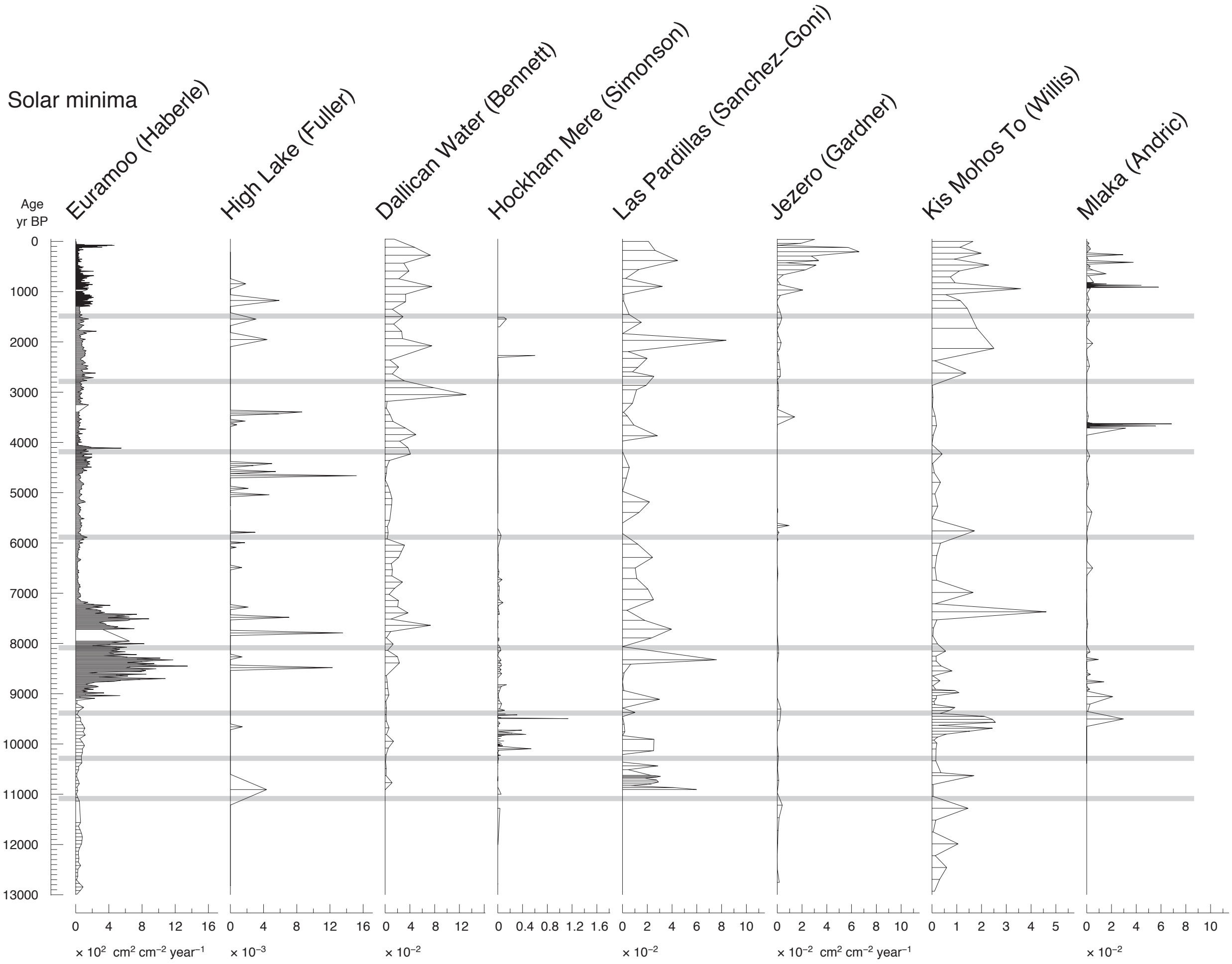


Fig. 4. The eight microfossil charcoal sequences with intervals of solar maxima (taken from Bond *et al.* 2001) indicated.

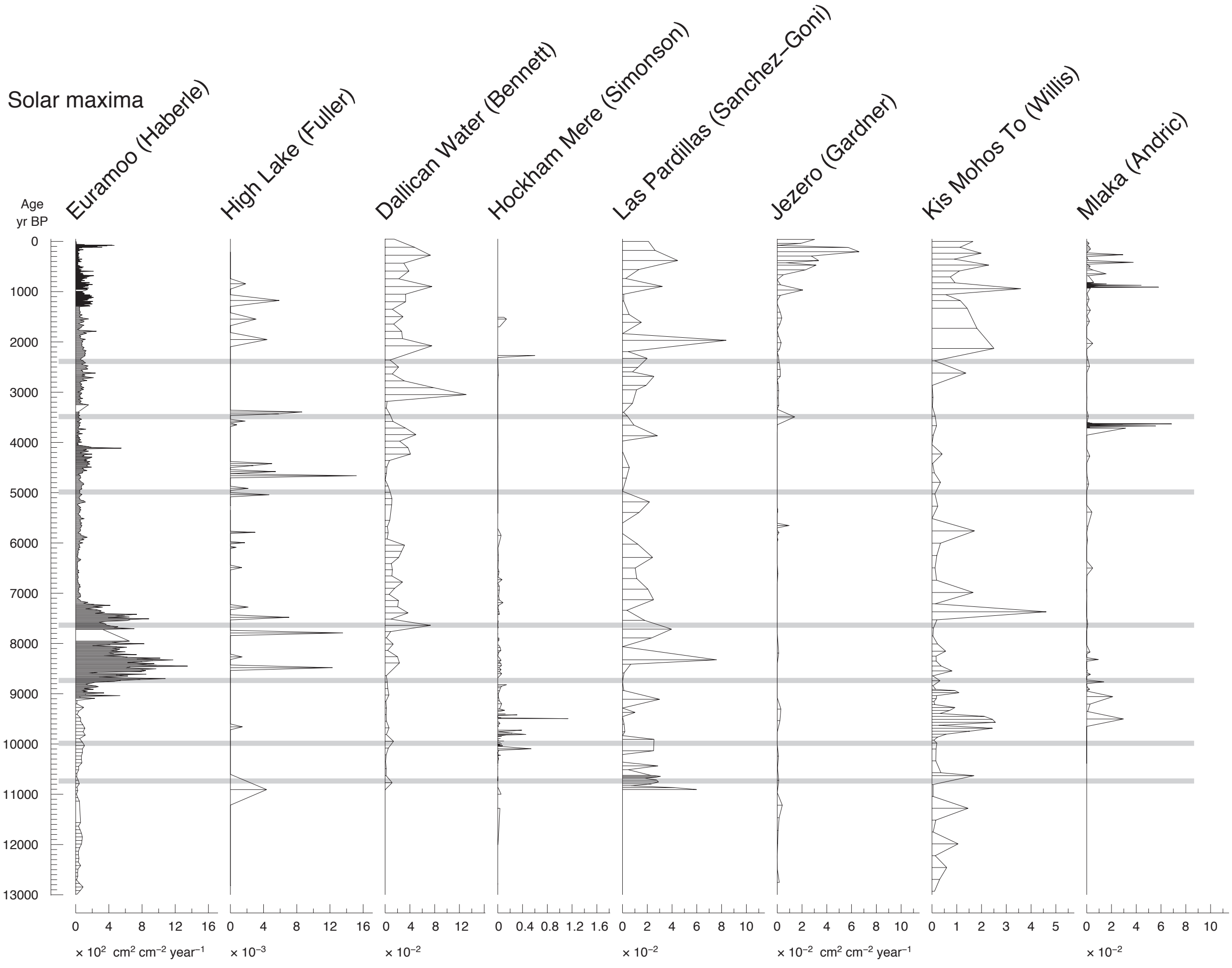


Table 5. Results of the chi-squared test between solar maximum/minimum and charcoal peaks (a) >3 standard deviations and (b) charcoal peaks >mean where values greater than 3.84 indicate that there is less than 5% probability that the association could have arisen by chance.

Site	(a)		(b)	
	Solar min	Solar max	Solar min	Solar max
Euramoo	0.13	4.50	0.13	0.02
Pardillas	1.03	1.02	0.21	0.91
Kis Mohos Tó	1.02	1.02	0.06	0.35
Mlaka	1.04	1.03	0.44	1.09
Dallican	1.04	1.03	0.09	0.31
Hockham Mere	1.09	2.96	0.43	2.41
High Lake	1.02	1.02	0.06	0.02
Jezero	1.02	1.02	0.48	0.03

also no statistically significant correlation.

Conclusions

The preliminary conclusion that can be drawn from this study is that at the eight sites examined there is no statistically significant relationship between Holocene solar variability (maxima or minima) and burning. But in drawing this preliminary conclusion, a number of other interesting results are also highlighted: First, that at every site examined the charcoal records indicate a specific structure suggesting distinctive burning events. Second, with the exception of two sites there is no obvious increase in burning frequency or intensity with increased human presence in the region. Third, that there appears to be little correlation between charcoal records from different regions. These three results together therefore suggest that burning, at least for the eight records studied, appears to be more strongly influenced by local abiotic and biotic factors than regional factors, and that burning events appear to be, on the whole, site specific (cf. Bennett *et al.* 1990).

So is it possible to identify predominant mechanisms responsible for burning regimes apparent in the Holocene sedimentary sequences? In order to rule out totally the influence of solar variability, it would probably be prudent to examine more ‘ecologically sensitive’ regions, for example the Near East and Mediterranean. Other palaeo-proxies for the 4.2 ka aridification event (one of the Bond minina) in the Mediterranean, for example, have indicated significant environmental change occurring around this event (Weiss & Bradley 2001) and this probably warrants further investigation. In terms of other factors influencing the burning regime, however, a similar approach to that demonstrated in this paper should be employed to examine associations between charcoal peaks and i) intervals of vegetation change (measured through rates of change), ii) species composition and iii) known intervals of human activity. By examining these associations it should then be possible to start to critically assess and test statistically the driving mechanisms responsible for Holocene burning regimes.

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