Climatically relevant periodicities in the thicknesses of biogenic carbonate varves in Soppensee, Switzerland (9740–6870 calendar yr BP)

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Abstract

Accurate determination of the thicknesses of 2717 biogenic carbonate varves from a Swiss lake (Soppensee), spanning the period from about 9740 to 6870 calendar yr BP, allowed the computation of a power spectrum using classical FFT methods. The presence of pronounced peaks at 40–50 and 20–25 yr agrees with the results of other studies on varve thickness and $\Delta^{14}\text{C}$ which have been interpreted as indicating an association between solar forcing and varve thickness. The presence in the Soppensee varve series of an additional peak at 10.9 yr, corresponding to the Schwabe sunspot cycle, lends further support to this hypothesis. Because the Soppensee varves are of biogenic rather than clastic origin, any influence fluctuations in solar irradiance may have had on sedimentation rates is likely to have been exerted via primary production.

Introduction

As early as the 1920s, Perfiliev (1929) emphasized the importance of periodic fluctuations in solar irradiance in determining the structure of laminated sediments. The detection of periodicities is best accomplished by spectral analysis; however, most measurements made on sediment cores are not easily amenable to classical spectral methods. Sampling intervals which may be equal with respect to sediment depth are unlikely to be so with respect to time, making spline interpolation or the employment of Lomb-Scargle techniques necessary. Although absolute dating accuracy is irrelevant for spectral analysis purposes, inaccuracies in relative dating result in unpredictable distortions in the Fourier representation of the data. The mechanical averaging resulting from analysing samples averaged over a variable or even unknown number of years acts like a low-pass filter with a non-stationary cut-off frequency, introducing random high-frequency atten-

uation into the spectrum. The decimation process resulting from the practical impossibility of analysing an entire core increases the mean sampling interval artificially, reducing the Nyquist frequency and subjecting the spectrum to increased aliasing. Of all measurements made on sediment cores, varve thickness, which is a direct record of annual sedimentation rate, is the most amenable to accurate spectral analysis. This is because the sampling interval (1 yr) is constant, well-defined and small, allowing the employment of classical Fast Fourier Transform (FFT) methods with relatively high accuracy and little aliasing. Relative dating inaccuracies are usually limited to those due to difficulties in matching the varves on adjacent thin-section microscope slides, so that such errors are unlikely to result in distortions at frequencies corresponding to periods less than the number of varves per microscope slide.

Anderson and Koopmans (1963), in their classic paper applying spectral analysis techniques to varve

thickness time series for the first time, described varve thickness records as imperfect meteorological time series that lend themselves particularly well to spectral analysis. Thus oscillations in climatic forcing affecting sedimentation rates (through clastic deposition or biological productivity) may leave a signal in the varve thickness record that is detectable by spectral analysis. Bracewell (1988) suggested that variations in solar ultraviolet and X-ray radiation affecting the ozoneosphere and ionosphere are the primary cause of varve thickness modulation. According to Zolitschka (1996), long-term shifts in varve thickness are due to changes in basin boundary conditions, whereas short-term changes are due to climate. Varve thickness determinations made in Lake Holzmaar, Germany (Zolitschka, 1996) show no correlation with precipitation or summer air temperature, but correlate negatively with winter and spring air temperatures and positively with autumn air temperature. According to Zolitschka (1996), no quantitative studies relating the thickness of biogenic, as opposed to clastic, varves to climatic factors are known. Thus a search for climatically relevant periodicities in biogenic varves is of great importance in attempting to elucidate the long-term influence of climate on lake ecosystems.

Determination of varve thickness

Determination of varve thickness requires well-defined laminations. Those found by Lotter (1989) in sediment cores from Soppensee, a small (surface area = 0.24 km², maximum depth = 27 m), hardwater eutrophic kettle lake located at 596 m a.s.l. in the central Swiss Plateau (47° 05' 30" N, 8° 05' E), are suitable for the purpose. The laminated portion of the Soppensee sediment record covers a timespan of about 6000 yr (Allerød to Atlantic) and consists of two series of siderite varves separated by a series of carbonate varves. This latter series, which extends from the Boreal to the Younger Atlantic, is the subject of the present study. The record analysed here is a section of Holocene sediment from core SO89-17, taken from the deepest part of the lake in autumn 1989 using a modified Kullenberg corer (Kelts et al., 1986) in the manner described by Lotter et al. (1997). It displays well-preserved light carbonate layers (spring/summer) alternating with dark organic layers (autumn/winter) spanning the period from 9739 (± 60) to 6869 (± 38) calendar yr BP. These varves are biogenic carbonate varves with no clastic component. Details on the

dating of the laminated sediment from core SO89-17 (AMS radiocarbon dating and varve counting) have been given by Hajdas (1993) and Hajdas et al. (1993), and a comparison of manual and automatic varve counting methods based on these varves has been described by Lotter & Lemcke (1999).

Thin sections were prepared on microscope slides as described by Lotter (1989). Computer images of the thin sections, obtained using a video camera attached to a binocular microscope, were analysed using an adaptation to the "Image Analyst™" program (Automatix Inc., Billerica, MA, USA) which allowed dark and light laminated layers to be distinguished by identifying the minima and maxima, respectively, of the grey function in the digitised image. The thickness of a varve was computed as the mean value of about 20 measurements of the distance between the two lines representing adjacent grey function maxima (i.e., the centres of two adjacent light layers), yielding a mean varve thickness with an error of about $\pm 2\%$. Measurements were made for segments of sediment 1–1.5 cm long with an overlap of about 3 mm between adjoining segments. Sediment depth in this core was then reconstructed using the measured varve thickness. This depth reconstruction was very good: over the core segment used in this study, the discrepancy between the reconstructed depth (101.4 cm) and the actual depth (100.7 cm) was less than 1%.

In the segment of varved sediment from core SO89-17 chosen for this study, there is a discrepancy of 153 varves between the 2870 annual laminations counted directly under a polarising petrographic microscope (Hajdas et al., 1993) and the 2717 varves identified by the computer program that determined the varve thicknesses. Varve counting represents a good relative dating method, and the validity of the Soppensee Holocene varve chronology has been demonstrated by Hajdas et al. (1993) using high-resolution radiocarbon dating and by comparison of the Soppensee chronology with that of the tree-ring chronology of Stuiver et al. (1986). In addition, the Soppensee varve chronology obtained agrees well with that of the Holzmaar series (Hajdas et al., 1995). The 153-varve discrepancy is therefore more likely to be a result of varves not having been identified as such by the computer program than of spurious additional varves appearing during varve counting by microscope (cf. Lotter & Lemcke, 1999). The scanned images used in computer counting lack some of the detail visible under the petrographic microscope, making precise identification of some laminae more difficult. In addition, varves can be "lost"

when matching up varve sequences between slides, because, despite the good quality of the laminæ, their somewhat wavy shape sometimes made it difficult to find a precise overlap. Thus there is a likelihood of hiatuses existing in the varve thickness record. Such hiatuses may cause distortions in the varve thickness spectrum; however, assuming the hiatuses to occur at the overlaps between adjacent microscope slides, they are unlikely to affect periods less than the number of varves per microscope slide. Therefore, for thin sections with about 50 varves per slide, distortion from this source is unlikely to have much effect on periods less than about 50 yr. Still, it is probably preferable to confine the employment of any spectrum obtained to confirming the existence of periodicities which might be expected on other grounds rather than to infer the existence of any new periodicities.

The time-series of varve thickness obtained is illustrated in Figure 1.

Spectral analysis of varve thickness

Spectral analysis of the varve thickness time series (the youngest 2560 of the 2717 varves) was carried out using the Welch (1967) Fast Fourier Transform (FFT) method. Individual spectra of five 512-point time series segments were computed with prior detrending and application of the Hamming window to each segment (yielding 5 degrees of freedom). Averaging over the spectra increased the number of degrees of freedom to 25, yielding the spectrum illustrated in Figure 2. Much power was present in periods exceeding ~ 100 yr; however, the spectrum decreased monotonically over this low frequency range, exhibiting no specific peaks at the given degree of resolution. The 15 most pronounced peaks in the spectrum are listed in Table 1. The first five of these occurred at 46.5, 24.4, 16.0, 13.5 and 10.9 yr. Power at periods less than 10 yr is concentrated in two regions; viz. 4.5–6.5 and 2–3 yr. Although the

Figure 1. Measured varve thicknesses from Soppensee, 9740–6870 calendar yr BP (grey), with 51-yr running mean (black). Note the logarithmic scale on the varve thickness axis.

Figure 2. Power spectrum of varve thicknesses from Soppensee, 9740–6870 calendar yr BP. Of the 15 most pronounced peaks (Table 1), the first five are labelled individually, whilst the higher frequency peaks are divided into two labelled groups. The 90% confidence interval is shown on the left.

peaks listed in Table 1 are barely significant at the 90% level, Anderson and Koopmans (1963) argue cogently that the application of classical Blackman-Tukey confidence interval estimation to varve thickness spectra can easily lead to labelling real spectral peaks as statistically insignificant. It will be shown that the first, second and fifth of the Soppensee peaks correspond well with peaks found in varve thickness spectra from lakes in other parts of the world, suggesting that these peaks may reflect generally relevant periodical physical forcing mechanisms.

Maximum entropy spectral analysis (MESA) confirmed the existence of five well-resolved peaks at periods greater than 10 yr corresponding approximately to those determined using the FFT method. Although the periods determined by 50th-order MESA for the first four peaks (51.6, 28.2, 17.4 and 14.2 yr) were

shifted somewhat with respect to those determined by FFT, the frequency shifts involved (0.002 – 0.005 yr^{-1}) were close to the resolution of the FFT spectrum ($\approx 0.002 \text{ yr}^{-1}$). The period of the fifth peak as determined by MESA (10.9 yr) agreed exactly with that determined by FFT.

Discussion

In a sequential power spectral analysis of the thicknesses of glacial and non-glacial clastic varves from a variety of sources, Anderson and Koopmans (1963) concluded that although strong periodicities are not a characteristic of varve series, weak periodic tendencies are almost always present. The weakness of these periodicities limits the usefulness of spectral analysis

Table 1. The periods of the 15 strongest peaks detected in the Soppensee varve thickness record (9740–6870 calendar yr BP)

Period [yr]	46.5	24.4	16.0	13.5	10.9	6.2	5.2	4.8	4.7	2.8	2.7	2.2	2.07	2.05	2.02
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as a purely exploratory technique; however, spectral analysis can still be useful as a confirmatory tool to search for the presence of specific periodicities that might be expected to appear for various reasons in a varve thickness record. Consequently, the possible existence of periodicities at 16.0 and 13.5 yr in the Soppensee record will merely be noted here, but will not be followed up further. Although Livingstone (1993) has noted the presence of a 12–16 yr periodicity in modern temperature data from the lower hypolimnion of Lake Zürich (50 km from Soppensee), there is no evidence of similar periodicities having been found in laminated sediments elsewhere, nor can a plausible explanation for the occurrence of such periodicities in the Soppensee sediments be given. The periodicities found at (i) 46.5 yr, (ii) 24.4 yr and (iii) 10.9 yr, however, agree with those found in other varve studies and may reflect real periodic climatic forcing.

(i) The strongest periodicity in the Soppensee varve record is that found at 46.5 yr. Although no convincing *prima facie* explanation can be given of why such a periodicity in varve thickness should be present, significant peaks at similar periodicities have been detected in many other laminated sediments in various regions of the globe. Anderson and Koopmans (1963), for instance, found a periodicity of 45 yr in a series of Jurassic limestone evaporite varves from New Mexico, and Ernesto & Pacca (1981) found a periodicity of 40–43.5 yr in Permocarboneous glacial rhythmites from Brazil. Spectral analysis of the thicknesses of varves from Lake Jüdesjön in northern Sweden by Renberg et al. (1984) spanning the period 230–1552 AD suggests the existence of a periodicity at about 30–40 yr, while Anderson (1992, 1993) found a period of 40–50 yr in varve thickness in Elk Lake, Minnesota over the last 8000 yr. This accumulation of evidence suggests the possible existence of a global forcing mechanism acting to modulate sedimentation at periods of around 40–50 yr. Such a hypothesis is supported by the fact that similar periodicities have been detected in other climate-relevant time series, e.g. in ^{10}Be concentrations in Greenland ice cores (Beer et al., 1994a), in tree-ring data on radiocarbon production (Stuiver, 1983; Stuiver & Braziunas, 1993) and in UK precipitation data (Tabony, 1979; Kane, 1988).

(ii) The periodicity at 24.4 yr is close to that of the 22-yr solar Hale cycle, well known to occur in drought and flood indices (e.g. Mitchell et al., 1979; Bhalme & Mooley, 1981; Stockton et al., 1983). Evidence of periodicities within the range 20–25 yr, suggesting that

solar activity may influence sedimentation, was found by Anderson and Koopmans (1963) in seven varve series, including Pleistocene glacial varves from a Canadian lake and Precambrian limestone varves from South Africa. Trendall et al. (1973) found evidence of a 23.3-yr periodicity in laminated Precambrian sediments in Australia. Anderson (1992, 1993) has found evidence of periodicity at 20–25 yr in the Elk Lake varve thickness time series, which he interpreted as a manifestation of the 22-yr Hale cycle. However, despite the proximity of the 20–25 yr periodicities found in these studies to the Hale cycle, the possibility of some or all of the power in this spectral region being due to a second harmonic of a non-sinusoidal 40–50 yr fluctuation cannot be ignored.

(iii) The 10.9-yr periodicity coincides with that of the Schwabe sunspot cycle (e.g. Cohen & Lintz, 1974). Periodicities corresponding to that of the Schwabe cycle have been detected in many time series in which fluctuations in solar irradiance might be expected to leave a significant signal, as well as in others in which such a signal might not at all be expected at first sight. These time series originate in various regions of the world and range from modern instrumental data on air temperature (Landsberg et al., 1959; Currie, 1974, 1979, 1993a; Landsberg & Kaylor, 1977), air pressure (Kelly, 1977; Currie, 1982), precipitation (Currie & O'Brien, 1990a,b, 1991, 1992; Currie, 1993b) and sea level (Currie, 1976, 1981a, 1991a; Woodworth, 1985; Currie et al., 1993) to data on the Earth's rotation and the length of the day (Currie, 1980, 1981b), ^{10}Be concentrations in Greenland ice cores (Beer et al., 1994a,b, 1996), tree-ring thicknesses (Mori, 1981; Currie, 1984, 1991b,c,d, 1992), floods (Currie & Fairbridge, 1985), earthquake frequency (Shaltout et al., 1992), agricultural and livestock production (Currie, 1988), wine harvests and fish catches (Currie et al., 1993), and even military engagements (Currie, 1988). In view of the extreme variety in the types of time series exhibiting a periodicity coinciding with that of the Schwabe cycle, it is perhaps not surprising that this periodicity should also be present in time series of varve thickness. Evidence for this in other varve series is sparse, but does exist. Although Anderson and Koopmans (1963) found no indication of such a periodicity in their comprehensive varve study, Anderson and Kirkland (1960) did detect a periodicity of 10–13 yr in the thickness of Jurassic varves in New Mexico. Also, Ernesto & Pacca (1981) found a periodicity of 11.5–12.0 yr in their Permocarboneous

rhythmites, and there is some evidence of a peak at about 11 yr in the spectrum of varve thickness in Lake Judasjön presented by Renberg et al. (1984). Zolitschka (1992) found a peak close to 11 yr in a varve thickness series from Lake Holzmaar, Germany.

In his recent detailed study of over 10,000 yr of varved sediments in Elk Lake, Minnesota, Anderson (1992, 1993) detected periods of 200, 40–50 and 20–25 yr in varve thickness and found that these tended to occur together. The same triple-peak structure also occurs in $\Delta^{14}\text{C}$ measured in tree-rings, implying that all three peaks may indicate an association between solar forcing and varve thickness (Anderson, 1992, 1993). Other evidence of similar periodicities in tree-ring data supports this suggestion. In Soppensee, the low-frequency resolution of the varve spectrum with 25 degrees of freedom depicted in Figure 2 is insufficient to detect any peak at 200 yr. Computation of spectra with 5 and 10 degrees of freedom (i.e. with much less statistical reliability but with correspondingly increased resolution) also failed to detect any peak near 200 yr, and in fact indicated that most of the low-frequency power was probably localised elsewhere (viz. at 350 ± 60 yr and 105 ± 5 yr). However, the presence in the statistically more reliable spectrum illustrated in Figure 2 of significant peaks within the 40–50 and 20–25 yr ranges lends support to Anderson's (1992, 1993) hypothesis of a solar influence on lake sedimentation rates. The mechanisms involved in Elk Lake and Soppensee, however, are unlikely to be the same. In Elk Lake, variations in palæowinds blowing loess into the lake appear to be responsible for the periodic variations in varve thickness (Anderson, 1992, 1993). In contrast, it can be speculated that the periodicities found in the biogenic carbonate varves in Soppensee are the direct result of periodic variations in biological productivity: Renberg et al. (1984), for instance, suggested that the 30–40 yr periodicity found in the Lake Judasjön varves was due to variations in the primary productivity of the lake associated with variations in the amount of insolation during summer. The presence in the Soppensee varve spectrum of a significant peak corresponding to the Schwabe cycle tends to support this interpretation. In order to investigate this more fully, it would be desirable to measure the summer and winter contributions to the annual varve thickness (i.e. the thicknesses of the light carbonate layers and dark organic layers, respectively) separately and compute two spectra; this would presumably lead to a better signal-to-noise ratio (implying an increase in the

statistical significance of the peaks already detected), since the processes principally responsible for sedimentation in the two half-years are qualitatively different. This would require determining the maxima and minima of the first derivative of the grey function of the digitised image of the varve sequence instead of the maxima and minima of the function itself.

Because of the ubiquitousness of high-frequency noise in geophysical time series, one should be careful in interpreting peaks in varve spectra at periods of less than about a decade. However, as in Soppensee, some evidence of increased power at periods of 4.5–6.5 yr has been found by Anderson & Koopmans (1963) in some glacial and evaporite varves, by Ernesto & Pacca in Precambrian rhythmites, and by Anderson (1993) in the sediments of Elk Lake. In Switzerland, a 5–6 yr periodicity has been detected in the temperature of the upper hypolimnion of Lake Zurich (Livingstone, 1993). Some of the power within the range 2–3 yr in the Soppensee varve spectrum may possibly be associated with the Quasi-Biennial Oscillation. Although the periodicity of the Quasi-Biennial Oscillation is 2.2 yr on average, it varies between 2 yr when sunspots are numerous to 3 yr when they are rare (Schove, 1987). Without further evidence, however, the geophysical relevance of the high-frequency peaks in the Soppensee varve series must be considered inconclusive.

Conclusions

Of all data obtainable from lake sediments, computer-derived measurements of varve thickness are potentially most useful in detecting periodic climatic forcing. Firstly, since varve thickness measurements can be automated to a large degree, they deliver more information per unit time invested than measurements of any other sedimentological parameter. Secondly, because the annual sampling interval is constant and small, varve thickness is much more amenable to accurate and reliable classical FFT spectral analysis than any other sedimentological parameter.

Classical FFT methods applied to biogenic carbonate varves from Soppensee revealed five pronounced peaks at periods greater than a decade. Of these, two (at 16.0 and 13.5 yr) have no counterpoint in varve series elsewhere and may be statistical artefacts. The remaining three (at 46.5, 24.4 and 10.9 yr) are at or close to periodicities that have been detected in other varve series, suggesting a common periodic forcing. The

existence of periodicities close to the Hale and Schwabe cycles suggests that fluctuations in solar irradiance may have influenced primary production and sedimentation in Soppensee. This is supported by Anderson's (1992, 1993) hypothesis of an association between the power found at 200, 40–50 and 20–25 yr in the spectra of $\Delta^{14}\text{C}$ measurements in tree-rings and that found at the same periods in the Elk Lake varve series.

Because there is a fundamental difference between the processes responsible for summer and winter sedimentation, future work on varve thickness series might profitably concentrate on attempting to measure the thicknesses of summer and winter laminae separately, thus allowing two separate spectra to be computed. This would presumably result in increased statistical stability, allowing peak resolution to be improved.

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