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HOLOCENE SOLAR VARIABILITY AND PELAGIC FISH PRODUCTIVITY IN THE NE PACIFIC

R. Timothy Patterson, Andreas Prokoph, Cynthia Wright, Alice S. Chang, Richard E. Thomson, and Daniel M. Ware

ABSTRACT

Many cycles recognized in the ocean sedimentary record have been linked to variable solar irradiance. This conclusion can be extended to include the paleoproductivity of fish stocks in the northeastern Pacific Ocean. Predominantly anoxic sediments from Effingham Inlet, Vancouver Island, British Columbia, collected from a 693 cm segment of a 1125 cm piston core, archive a high-resolution late Holocene (1,800-4,700 years BP) record of climate-change and paleoproductivity in the North American Coastal Upwelling Domain (CUD). Fish-scale abundances of Northern Anchovy and Pacific Herring were measured in this core. Spectral analysis (SA) and continuous (Morlet) wavelet transform (CWT) analysis of the dataset were used to examine fish productivity cycles and their variability within the absolute time scale. Anchovy and herring populations cycle independently at decadal to centennial scales, with especially well-defined variability at the stationary Gleissberg solar cycle (75-90 years here). Several other cycles are non-stationary, changing frequency following transition of the regional climate to a higher rainfall phase that impacted coastal oceanic dynamics ~ 3,400 years ago.

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Figure 1. Location map of Effingham Inlet, Vancouver Island, British Columbia, Canada.

INTRODUCTION

Sub-decadal climate variability in the Pacific Ocean is affected by interdependent variability in the Aleutian Low (AL), North Pacific High (NPH), the Jet Stream, and the equatorial El Niño/La Niña cycle. Superimposed on this variability are less well-understood, regionally modified, decadal and centennial scale cycles that appear to arise from global-scale teleconnections (Mann et al. 1995; Ware and Thomson 2000). There is also a growing body of empirical evidence that there is correlation between climate records and solar and cosmic ray activity and their proxy indicators (e.g., geomagnetic field activity, sunspot numbers, and ^{10}Be, ^{36}Cl, ^{14}C abundances) suggesting that extraterrestrial phenomena may be responsible for at least a portion of climate variability (e.g., Bond et al. 1997; Bond et al. 2001; Kromer et al. 2001; Neff et al. 2001; Sharma 2002; Hu et al. 2003; Usoskin et al. 2003).

The instrument record is barely adequate for analyzing characteristics of decadal-scale Holocene climate cycles, including cycles linked to climate change events such as the well-publicized collapse of west coast North American commercial fisheries (Hare et al. 1999). Because long-term trends in regional and global temperatures are modified by low-frequency events that are difficult to resolve with relatively short historical records, a more complete understanding of the dynamics of natural climate variability as well as medium and long-term climate oscillations can only be achieved by turning to the geological record.

Changes in productivity in Effingham inlet, southwest coast of Vancouver Island, British Columbia, Canada (Figure 1, Figure 2) are represented in the sediments by variation in the relative thickness of the seasonally deposited laminations of diatom-ooze and terrigenous material. These variations, in turn, can be linked to changing ocean climate conditions (McQuoid and Hobson 2001).

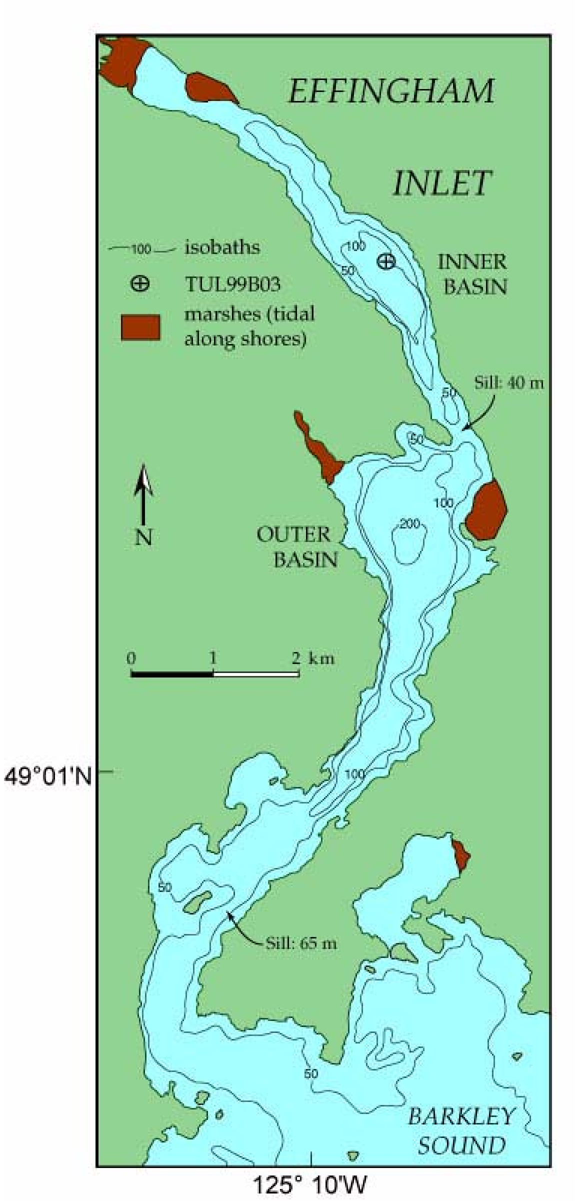

Figure 2. Close-up isobathymetric map of Effingham Inlet showing location of core TUL99B03.

The clockwise circulating NPH dominates the NE Pacific region in the summer resulting in cool and dry northerly winds, while the anticlockwise circulating AL dominates during winter, generating warm and moist southerly winds (Thomson 1981; Beamish 1993; Mantua et al. 1997; Ware 1991; Ware and Thomson 1991, 2000; Figure 3). Seasonally dependent upwelling (caused by NPH wind-driven, Ekman transport of surface waters

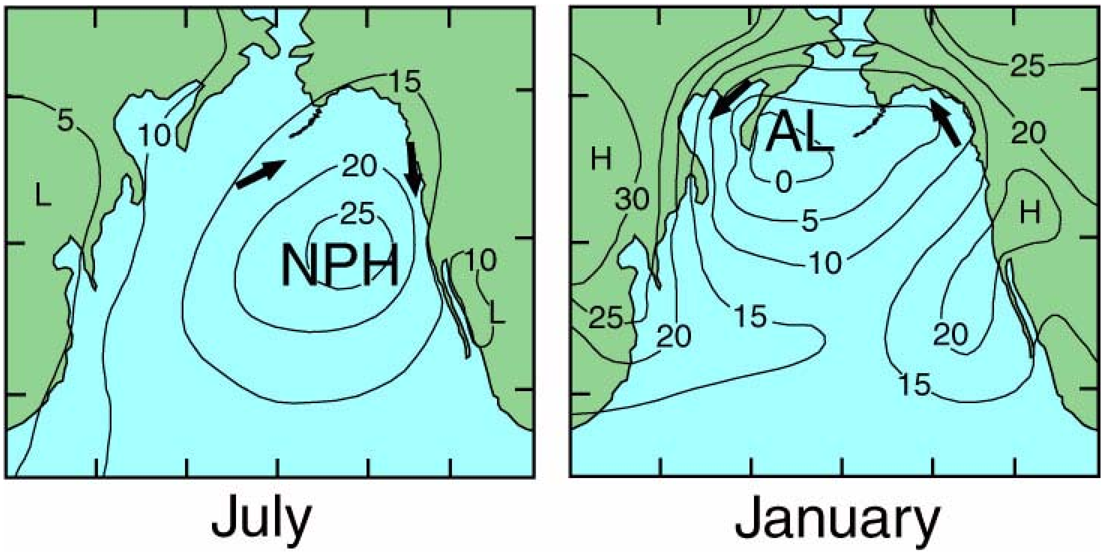

Figure 3. Air pressure at sea level in July and January for the northeast Pacific region. In winter, when the continental land mass is cold and the ocean relatively warm, a large-scale counterclockwise low pressure gyre (the Aleutian Low [AL]) develops, dominating the weather of the entire northeastern Pacific. In summer when the land mass is hot and the ocean relatively cool, a large-scale clockwise high-pressure cell (North Pacific High [NPH]) moves up from the south to dominate the weather in the northeast Pacific. Arrows indicate prevailing wind direction. Values on the diagram +10,000 divided by 10 gives pressure in millibars (modified after Favorite et. al. 1976).

away from the Vancouver Island continental margin, usually between May and August at present) is the principal mechanism providing nutrient supply to the coastal ocean off southwest British Columbia (Thomson and Gower 1998; Figure 4). Over time, changing climatic conditions impact the AL and NPH, leading to changes in surface wind stress, regional circulation, mixed layer depth, and stratification. These changes may be at least partially the result of extraterrestrial climate forcing, because there is a link between the 11-year Schwabe sunspot cycle and the centers of action of both the AL and NPH (Christoforou and Hameed 1997; Hameed and Lee 2003). The influence of extraterrestrial climate forcing through centennial to millenial-scale cycles are magnified by as much as a factor of four (Carslaw et al. 2002).

Changing climatic conditions in the NE Pacific in turn, modify the surface layer of the ocean where phytoplankton growth is concentrated (Brodeur and Ware 1992). This drives cyclical changes in primary production, timing of blooms and phytoplankton assemblages (Ware and Thomson 2000). Because pelagic fish respond to food availability, these changes cascade through the various trophic levels eventually impacting commercially important pelagic fish populations (Beamish and Boillon 1993).

The purpose of this research is:

1. To determine the implications of the observed fish productivity cycles and the temporal variability in fish-scale abundances of two particularly abundant taxa, Pacific Herring and Northern Anchovy, in Core TUL99B-03 from the inner basin of Effingham Inlet (Figure 2). Both Pacific Herring and Northern Anchovy undergo significant periodic population fluctuations. However, because of the brief modern fishing records, the frequency and amplitude of longer term changes are largely unknown (Holmgren-Urba and Baumgartner 1993; Schweigert 1995; Tunnicliffe et al. 2001).
2. Demonstrate the relevance of paleontological analysis in ecological studies. Paleontology is advantageous in ecological analysis because the duration of most biology-based ecological studies are too short to assess the long-term impact of either anthropogenic or natural perturbations on biological communities (Martin 1991, 1995; Martin et al. 1999; Jackson 1992; Aronson and Precht 1997; Kowalewski et al. 1999).

Our analysis is also intended to bring the continuous wavelet transform time series analysis methodology (described in more detail below) to the attention of the paleontological community, which has had little exposure to this useful way of dealing with non-stationary cycles in biostratigraphic records (Prokoph et al. 2000, 2001).

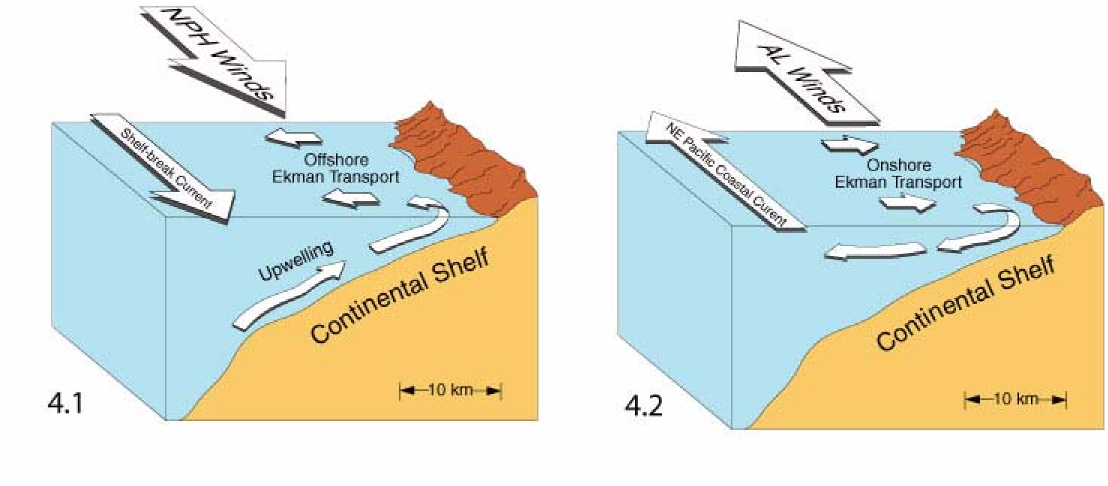

Figure 4. 4.1. Main features of the upwelling-favorable wind conditions off west coast of Vancouver Island during the summer. Northerly North Pacific High (NPH) winds generate a southward surface flow and a consequent offshore Ekman transport inducing upwelling. **4.2.** Main features of wind-induced downwelling off the west coast of Vancouver Island during the winter. Southerly Aleutian Low (AL) winds generate a northward drift and a consequent onshore Ekman transport (modified after Thomson, 1981).

Pacific Herring and Northern Anchovy Ecology

Pacific Herring (*Clupea harengus pallasi*) is a cool water species (Figure 5). When annual water temperatures are below average, the typically plentiful herring stock around Effingham Inlet increases in abundance (Ware 1991; Schweigert 1995). In contrast, the Northern Anchovy (Figure 6) is typically at the northern limit of its range in British Columbia. Anchovy are more productive in this region when upwelling is suppressed and sea surface temperature (SST) is elevated (Richardson 1981). In the absence of major biotic factors such as predation and overfishing recruitment, mortality rates and abundance of anchovy and herring populations around Effingham Inlet should vary in opposition to one another as a function of changes in upwelling and SST conditions. Alongshore advection may also play a role because upwelling-favorable southerly winds give rise to southward mean currents over the slope and outer shelf, while downwelling-favorable northward winds cause northward mean currents in the region.

Pacific Herring

BC herring populations are spring spawners (March/April) and tend to spawn at temperatures around 7-8ºC. Recruitment to the West Coast of Vancouver Island herring population tends to be much lower when ocean temperatures are warm. Accordingly, the abundance of this population declines and tends to be well below average during warm periods. In contrast, average recruitment to this population is twice as high during cool periods,

Figure 5. 5.1. *Clupea harengus pallasi* (Pacific Herring); sketch of modern living specimen; length = 46 cm. **5.2** Modern *Clupea harengus pallasi* (Pacific Herring) scale; body region C; scale bar = 1.0 mm. (After Patterson et al., 2002.)

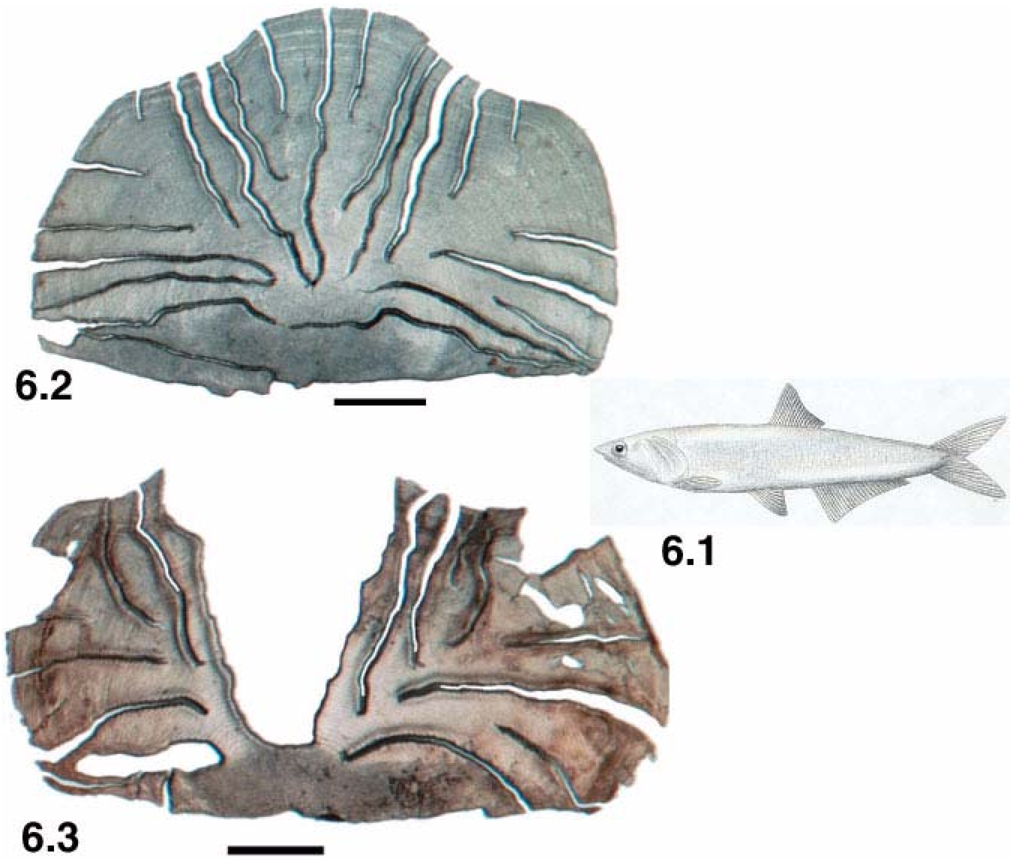

Figure 6. 6.1 Engraulis mordax mordax (Northern Anchovy); sketch of modern living specimen; length = approximately 18 cm. **6.2.** Modern Engraulis mordax mordax (Northern Anchovy) scale; scale bar = 1.0 mm. 6.3. Subfossil Northern Anchovy scale, core TUL99B03, interval 30-40 cm; scale bar = 1.0 mm. (After Patterson et al., 2002.

so the population becomes more abundant (Ware 1991; Ware and McFarland 1995).

Northern Anchovy

Northern Anchovy are distributed from Magdalena Bay, Baja California to the Queen Charlotte Islands, BC. This species is at the northern end of its range in BC. Anchovies appear to prefer water temperatures between 14.5 and 18.5ºC (Hart 1973).

In the NE Pacific, three populations of anchovy are recognized: the northern (Oregon/Washington/BC), Central (California/Mexico) and Southern (Mexico).

A large component of the northern population of anchovy spawn in waters around the Columbia River plume. Spawning conditions differ between the northern and central populations of anchovy. "Off Oregon, spawning occurs from mid-June to mid-August, when current flow to the south is at a maximum, *water temperatures are reaching maximum levels for the year, coastal upwelling is at a maximum,* and day length is at or near maximum duration. Off California, peak spawning occurs from January through April when southward current flow is minimal, water temperatures are reaching minimal levels for the year, upwelling is minimal, and day length is at minimum duration" (Richardson 1981).

Hart (1973) states that in BC the life history of anchovy "is not well known and occurrence is sporadic." He also notes that anchovies are "not available abundantly or consistently enough in British Columbia to be used commercially" except during a brief period of abundance in the Strait of Georgia in the early 1940s.

An article in the Pacific Biological Station Progress Report (1945) 63:41 states that "the Northern Anchovy is found in large schools along the British Columbia coast during the spring and early summer." In BC, anchovy are summer spawners. They require water temperatures above 13ºC for successful reproduction. These conditions only occur in a few places in BC and only in the summer (July and August; Hart 1973). Although water temperatures have been above normal around Barkley Sound since the mid 1970s, the abundance of the anchovy population in the Barkley Sound area has been relatively small. Therefore, other important factors besides warm summer temperatures are required for the successful reproduction and expansion of the local anchovy population around Effingham Inlet (see below). It is unknown whether the Barkley Sound anchovy population is self-sustaining (and somewhat genetically distinct), or whether it is sustained by a periodic influx of migrants from the much larger Columbia River population to the south. Genetic samples would have to be taken to determine if the Barkley Sound population is relatively isolated, or if it mixes with, and is therefore genetically indistinguishable, from the Columbia River population. Because the fish-scale record suggests that Effingham Inlet always contains some anchovies, if this small, local population disappears periodically it must be recolonized fairly quickly by migrants from nearby populations.

An analysis of ocean climate time series off the SW coast of Vancouver Island for the period 1930-45, when anchovies were abundant in BC, indicates that during this period, upwelling favorable winds in the summer (mean JJA wind stress = 0.151 dyn/cm^2) were anomalously low (–0.7 standard deviations below the long-term mean JJA wind stress = 0.223; SD=0.106; Hsieh et al. 1995). During the same period, the summer (JJA) SST was average (a mixture of warm and cool years; DFO Lighthouse data). Therefore, the data clearly indicate that summer upwelling (and, coincidentally, southward alongshore coastal currents) was anomalously weak when historical sources reported that anchovy were abundant in southern BC. Consistent with this interpretation, anchovy have not been abundant in BC since the early 1940s, and coastal upwelling in the summer has not been as weak as it was during that period (Hart 1973; Therriault et al. 2002).

A northward shift in the sea surface temperature isotherms during the spawning season (particularly during warm El Niño years such as 1982/83), causes the distribution of the central anchovy population to shift northward (Fiedler et al. 1986). By analogy, the distribution of the northern population may also shift northward into BC during anomalously warm summers.

Richardson's (1981) paper provides evidence that warm water temperatures are necessary for the successful reproduction of the northern population of anchovy. However, warm summer temperatures alone are not a sufficient condition.

Research summarized by Ware (1991) and Ware and McFarland (1995) indicates that the West Coast of Vancouver Island herring population increases in abundance during cool periods and declines during warm periods. Since the herring and anchovy populations around Effingham Inlet should vary in opposition to one another, this *implies* that ocean conditions were probably warmer than normal when anchovy were dominant. Historical data also indicate that anchovies were more abundant in BC when summer upwelling was anomalously low. It is also important to appreciate that changes in the abundance of fish scales in a single sediment core could also reflect changes in migration/distribution patterns. Extensive research confirms that the herring around Effingham Inlet do not migrate large distances. They migrate seasonally to offshore feeding banks in the summer, and return inshore in the late Fall to over-wintering areas near the spawning grounds (Taylor 1964). Consequently, a large increase in herring scales in Effingham Inlet most likely reflects an increase in the productivity of the West Coast of Vancouver Island herring population.

In contrast, under some conditions, it is possible that anchovy could migrate northward from the main spawning area off the Columbia River to the West Coast of Vancouver Island in the summer to spawn and to forage. Consequently, a high abundance of anchovy scales in Effingham Inlet could reflect either: 1) an increase in the abundance of the local population, or an increase in the abundance and northward expansion of Columbia River anchovies (note that in both cases, the increase in abundance arises from an increase in anchovy productivity either locally or to the south of Barkley Sound); or 2) a change in the summer distribution pattern of Columbia River Anchovy. For example, when summer upwelling is extremely weak, anchovy off Washington may migrate northward to southern BC in search of food.

Scale Preservation

Engraulis mordax mordax (Northern Anchovy)

Scales of the northern anchovy preserve easily in Quaternary sediments (Figure 6). They are robust and have a high degree of mechanical flexibility. They are, however, subject to erosion and fracturing along points of weakness (Figure 6). The degree of abrasion in the sediments controls the degree of fragmentation. Wings (posterior fields) are often disarticulated, as is the central lobe in the anterior field. In some cases, all three lobes and wing are disarticulated, leaving only the central focal area. Care must be taken when determining counts so that a single fragmented scale is not counted several times. The scales are generally amber in color. Some geochemical conditions can

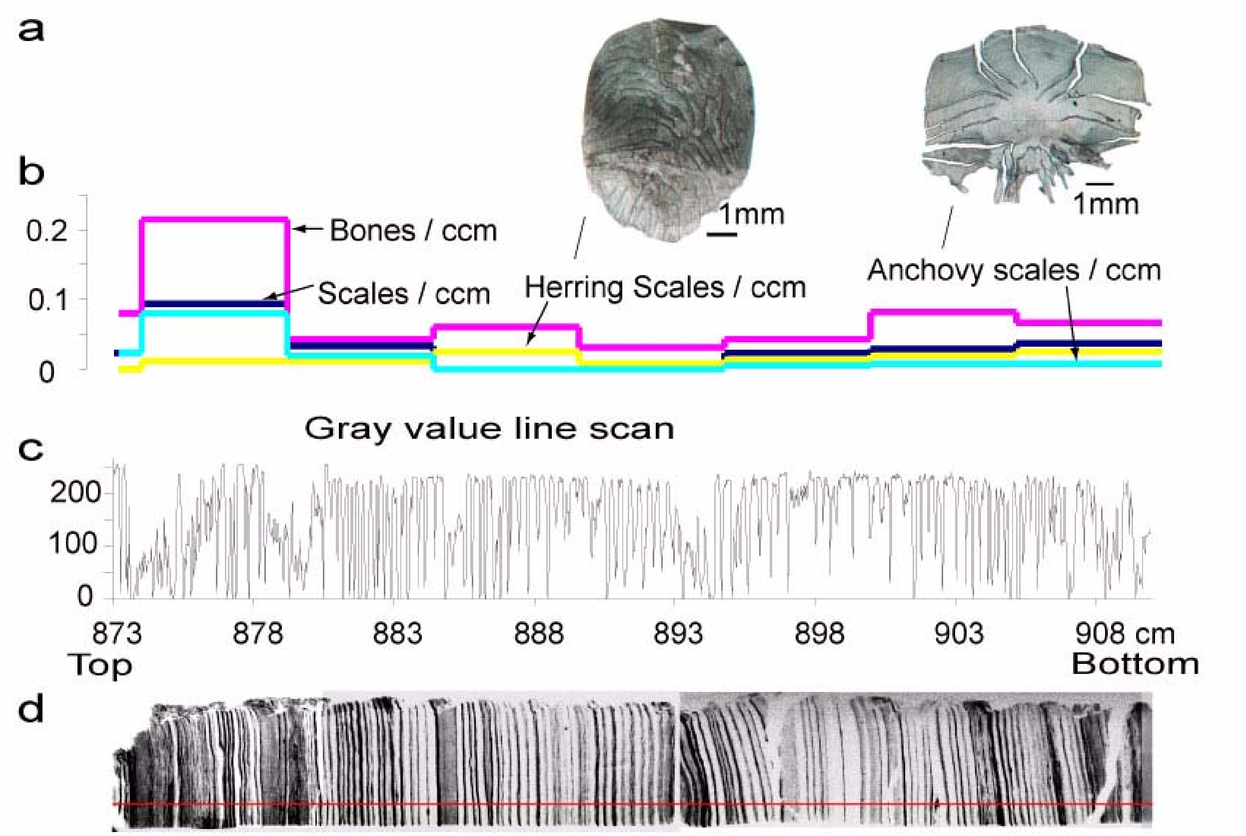

Figure 7. Fish-scale abundance and x-ray coloration for the laminated core interval from 873-910 cm of core TUL99B03. (**a**). Herring and anchovy fish scales. (**b**). Record of fish scales and fish bones/cm^3. Note that anchovy scales are more common in dark sediments. (**c**). Gray-scale values derived from scan along red line in x-ray segment (**d**), where a value of 255=white and 0=black.

"bleach" them white and cause them to become extremely brittle (Patterson et al. 2002).

Clupea harengus pallasi (Pacific Herring)

Clupeid scales are, comparative to other fish species, thick and robust and therefore preserve easily in Quaternary/Holocene sediments (Figure 5). Because of their robustness, herring scales tend to preserve whole, sometimes even with the posterior field (wing) attached (Patterson et al. 2002). That generality aside, *Clupea* scales tend to rip and break at fracture areas. The leading edges of the anterior field and the wing clips are also often detached. As a result it can often be quite difficult to distinguish *Clupea* and *Sardinops* fragments. However, *Clupea* scales (including the wings) are generally white and quite mechanically flexible, and to some extent easily ripped, while *Sardinops* scales are often amber and brittle.

The Data

Our dataset comprised measurements of laminae thicknesses and laminae gray-scale values extracted from x-ray images of annually deposited sediments, as well as fish-scale abundances (Figure 7). We applied two time series analysis tools (CWT and SA) to our dataset in order to overcome limitations inherent to each (Emery and Thomson 2001). CWT has advantages over SA in that it determines the frequency content of time series as a function of time. If temporal changes occur in frequency and phase of time series (i.e., time series are non-stationary), we can recognize and quantify them using CWT analysis. On the other hand, SA provides us with estimates of the "power" (signal variance per unit frequency band) as a function of frequency, as well as estimates of the cross-spectral power between two time series (Davis 1986). The combined result is a more robust and quantitative periodicity analysis.

METHODS

Our data set of digitized laminae thickness, and gray-scale variation, relates directly to annual precipitation (winter terrigenous laminae) and annual productivity (summer diatom laminae). The darker terrigenous laminae, consist of silt, organic

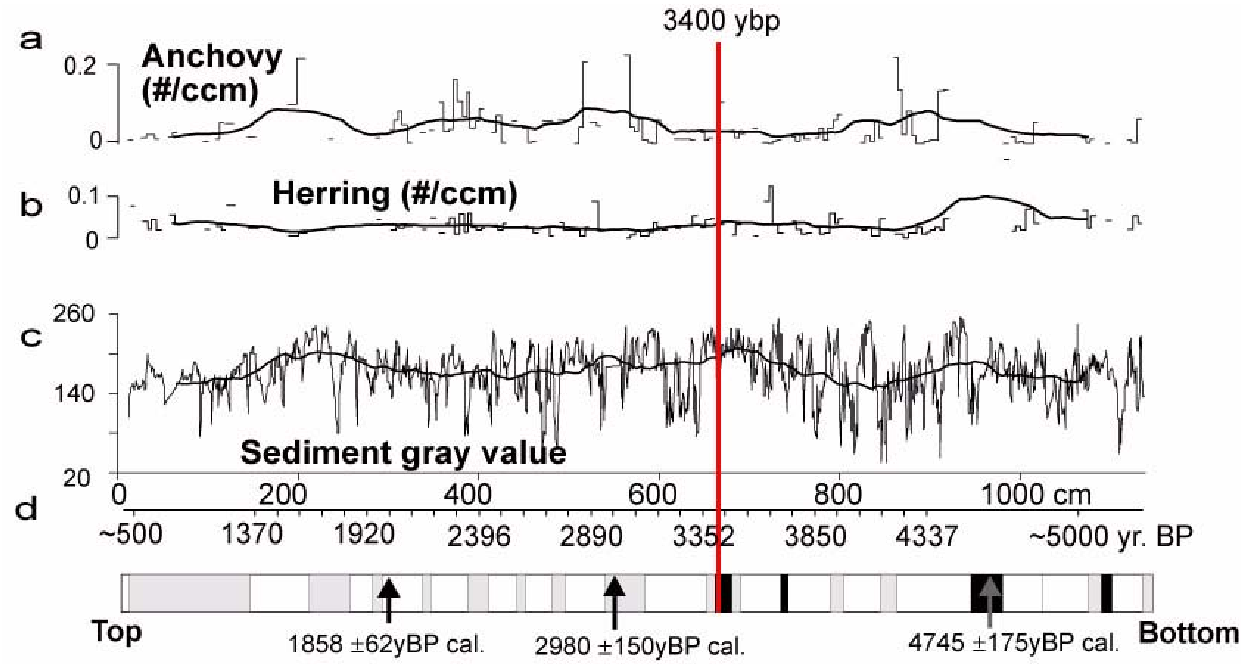

Figure 8. Core TUL99B03 from 0-1230 cm below sea bottom. (**a**). Anchovy record (scale counts/cm^3) including a 2 m moving average (bold line). (**b**). Herring record (scale counts/cm^3) including a 2 m moving average (bold line). (**c**). Sediment gray-scale value (derived from x-ray images) including a 2 m moving average (bold line). X-ray images were scanned at 256 gray-scale values to produce 130,787 vertically measured pixels based on a ratio of 116 pixels = 1 cm; 1 data point = 100 pixels, resulting in 1309 data points. As a result of lost core or poor image quality, 7.4 % of the data was deleted. Data loss was minimized because line scans of the core were carried out in three parallel line scans that permitted the negative impact of cracks in the core and other gaps to be minimized. (**d**). Time-scale derived from linear regression of three calibrated ^{14}C ages. Note that the time-scale on top and bottom of core is uncertain, and ages are extrapolated. Generalized core lithology with white intervals representing well-laminated sediments, gray intervals represent poorly-laminated core intervals, and black intervals represent non-laminated, or otherwise disturbed laminations (e.g., as a possible result of seismic shaking).

debris, and robust diatoms are deposited during the rainy winter months when there is increased runoff. The lighter laminae are comprised primarily of diatoms frustules and are deposited from spring through fall when productivity is enhanced (Chang et al. 2003; Figure 8). The relative thickness and color of laminae vary over time in response to changing environmental conditions. Gray-scale analyses of these changes provide an extensive time series that can be used to track this climatic and oceanographic variability (Figure 7, Figure 8). The abundance of fish scales of Northern Anchovy and Pacific Herring in the core have been used in association with the sedimentological data to compile an additional time-series.

Independent confirmation that the observed laminations represent annual deposition has been provided by detailed ^{14}C and diatom analysis of core TUL99B-03 (Table 1) as well as detailed diatom analysis and ^{137}Cs and ^{210}Pb dating of the 120 cm freeze core (TUL99B-04) collected nearby (Chang et al. 2003). Physical measurement of annual laminae and accurate ^{14}C ages (Figure 8) indicate that sedimentation rate was nearly constant throughout the studied interval (Dallimore 2001).

Detailed sedimentological and ^{14}C analysis of seven piston cores collected within adjoining basins of Effingham Inlet as part of a larger study revealed similar stratigraphic successions (Dallimore 2001), so that the patterns recognized in piston core TUL99B-03 are consistent with actual depositional conditions. The upper 280 cm of the core (which was deposited after ~ 1,800 y BP) was not analyzed here because this portion was very unconsolidated, resulting in poor recovery of sedimentary laminations. Similarly, the lower 150 cm of the core was not analyzed because of loss of record continuity from massive intervals and earthquake-related sedimentation disruptions (Dallimore 2001).

Mathematical-Statistical Methods

We applied continuous wavelet analysis, spectral analysis, and cross-spectral analysis to our datasets in order to quantify the trends, cyclic-

Table 1. Radiocarbon dates obtained for core TUL99B03. Results are reported in years before present (BP), as well as calibrated years BP (cal BP). As can be expected, the calibrated results increase the uncertainty of the date. Dating and calibration was carried out by the Isotrace Laborabory at the University of Toronto in comparison with the dendrochronologically derived INTCAL98 dataset for terrestrial material (Stuiver and Braziunas 1993; Stuiver et al. 1998).

Sample Number	Dated Material	Lithology
RC03S301	Twig 135 mg	laminated
RC03S501	Twig 545 mg	laminated
RC03S701	Wood 562 mg	massive

Sample Number	Isotrace Number (U. Toronto)	Depth in Core (cm)	BP	CAL BP
RC03S301	TO-8673	286	2050±70	1858±62
RC03S501	TO-8674	553	2830±60	2980±150
RC03S701	TO-8676	937	4190±80	4745±175

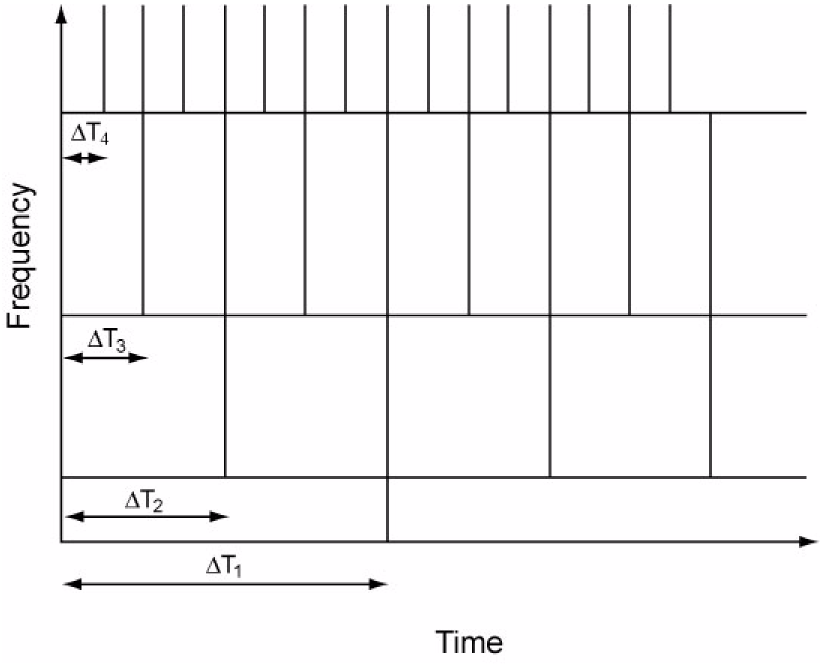

Figure 9. Cartoon showing how continuous wavelet analysis can be used to examine time series data at many different time (e.g., ΔT_1, ΔT_2, ΔT_3, ΔaT_4) and frequency scales simultaneously. The method also permits recognition and temporal placement of data trends including both continuous and discontinuous cycles.

ity, and bandwidth dependent relations between the different time-series. We used the percentages of taxa present rather than the absolute values in most of the time-series analyses.

Continuous Wavelet Transform Methodology

Continuous wavelet transforms are mathematical correlation functions that partition data series into different frequency components as functions of time (Figure 9). Each component is then studied at a resolution appropriate to its time- or depth scale (Graps 1995). By examining the entire data set over all frequency bands any cyclic patterns contained in the data series can be identified. This approach is not new. Fourier (1822) discovered that any function can be closely approximated by a superposition sines and cosines. What is novel about the CWT is the simultaneous function approximation in both time- and frequency-scales, using variable analysis window sizes. Analysis of a signal with a long time (or depth) window permits for high resolution of the frequency content of the data, revealing gross features in the time series. In the case of stratigraphic data, such long windows are needed for low-frequency cycles spanning longer time periods. Analysis of signals with a short time (or depth)l window permits low resolution or shorter duration feature in the frequency pattern. In the context of analyzing stratigraphic data this characteristic permits recognition of high-frequency cycles or abrupt 'jumps' (caused by unconformities, sequence boundaries, etc.). CWT is therefore ideal for identifying the patterns typically found in stratigraphic geological data. Wavelet coefficients can also be plotted along a time axis permitting easy recognition of cycles or discontinuities in the data time and frequency scales. Since CWT operates at all scales researchers can "see both the forest and the trees (Graps 1995)," a characteristic well suited to geological research.

In contrast the sines and cosines that form the basis for Fourier analysis are non-local, and by definition stretch out to infinity. They are useful for examining the frequency content of stationary processes but not useful for approximating the sharp breaks in geological data described above. Wavelet analysis addresses this problem by using approximating functions that are contained in variably scaled finite domains, but has the disadvantage that 'edge effects' (suppressed magnitudes for low frequencies) occur for wavelet coefficients at the top and bottom of any analyzed time series. Wavelet analysis is limited by the Uncertainty Principle whereby higher resolution in time means lower resolution in frequency, and vice versa (Emery and Thomson 2001).

For a time series, $f(t)$ CWT produces a space of wavelet coefficients $W_\psi(a, b)$, of scale (e.g., wavelength) a and time (or depth) b:

$$W_\psi(a,b) = \left(\frac{1}{a}\right) \int f(t)\, \psi\left(\frac{t-b}{a}\right) dt \quad .(1)$$

We used the Morlet wavelet (scaled and translated)

$$\psi^{l}_{a,b}(t) = \pi^{-\frac{1}{4}} (al)^{-\frac{1}{2}} e^{-i2\pi\frac{1}{a}(t-b)} e^{-\frac{1}{2}(\frac{t-b}{al})^2} \quad (2)$$

with l representative of the scaling ratio of the analyzing window, which is set to l=10 providing particularly good resolution in periodicity (Rioul and Vetterli 1991; Grossman and Morlet 1984). Using "zero-padding" on the beginning and ends of the data series reduced edge effects of W. Data were standardized to a mean = 0, and a fitted linear trend line was removed. The graphic representation in the time-frequency space is a "scalogram."

Squared Coherency Calculation

To test the confidence of cross-spectral analysis we carried out a squared coherency calculation at the 95% confidence level. Using the approach of Emery and Thomson (2001), we divided the fish-scale time-series into successive blocks (roughly 3) with 50% overlap and applied a Kaiser-Bessel weighting to the time series prior to applying the Fast Fourier transform (FFT). For this filter, 50% overlap is sufficient to create individual blocks that are essentially independent time series. In the frequency domain, we used band-averaging of adjacent frequency (f) bands such that df/f = 0.2 for all frequencies. There are about 6 degrees of freedom (DOFs) per band, except at high frequencies where df becomes large, and the confidence interval becomes smaller. We applied spectral analysis using FFT and coherence (frequency domain) analysis on the fish-scale data and assumed locally uniform spectral levels for estimation of confidence interval estimates. Squared coherency and 95% confidence level indicate that the slight increase of cross-spectral amplitude at high frequencies in the herring-anchovy time-series observed with spectral analysis is not significant.

Fish Scales

Fish scales were well preserved in these sediments, and abundances were measured as the number of scales/cm^3 of sediment (Table 2). To avoid over-counting of fragmented specimens, only scales with intact focal points were included in the analysis.

RESULTS AND DISCUSSION

We performed CWT and SA analysis on fish-scale remains in 66 sample horizons in core TUL99B-03. Ten species of fish were documented, with Pacific Herring and Northern Anchovy being the most abundant. We required 3-10 cm of core per sample to obtain sufficient fish-scale material. For this sample size, the effective Nyquist sampling interval (Davis 1986) obtainable for CWT and SA was 17 cm, giving a ~60 year temporal resolution (Figure 8). Thus, only cycles with periods greater than 60 years could be considered reliable. As indicated by Figure 10 and Figure 11 70- to 110-year cycle, corresponding to the well-documented Gleissberg Cycle (Garcia and Mouradian 1998), is a predominant influence on both Northern Anchovy and Pacific Herring populations throughout the sampled intervals. Cycles attributable to the Suess cycle are also present in the fish-scale record (Figure 10, Figure 11). The 200-year Suess Cycle (Sonnett and Finney 1990) has been linked to the Maunder Minimum of the Little Ice Age, and corresponds to other Maunder-like minima with the same 200-year period in Mid-Holocene sediments

Table 2. Pacific Herring and Northern Anchovy/cm^3 results from 280-960 cm in core TUL99B03 as utilized in Figure 7.

Depth interval	#Herring Scales/cm^3	#Anchovy scales/cm^3	#scales/cm^3
287-292	0.045	0.013	0.136
302-307	0.019	0.033	0.1
307-312	0.026	0.058	0.094
312-317	0.022	0.08	0.147
317-322	0.029	0.047	0.089
359-364	0.011	0.102	0.122
365-370	0.035	0.03	0.075
370-375	0.048	0.037	0.11
380-385	0.058	0.108	0.173
385-389	0.014	0.066	0.094
389-392	0.06	0.128	0.256
392-397	0.025	0.039	0.07
397-402	0.019	0.055	0.077
416-421	0.03	0.028	0.064
421-426	0.018	0.071	0.1
426-431	0.036	0.003	0.041
438-443	0.025	0.055	0.08
460-465	0.01	0.005	0.031
473-478	0.026	0.055	0.115
478-483	0.006	0.055	0.113
489-494	0.037	0.058	0.186
507-512	0.019	0	0.033
512-517	0.005	0.042	0.092
525-532	0.089	0.053	0.412
532-537	0.016	0.045	0.076
563-568	0	0.221	0.636
568-573	0.008	0.042	0.071
573-578	0.019	0.03	0.064
583-588	0.006	0.008	0.034
588-593	0.014	0.003	0.03
593-598	0.037	0	0.037
603-608	0.018	0.045	0.076
631-636	0.028	0.011	0.044
656-661	0.047	0.013	0.079
680-685	0.008	0.034	0.047
685-690	0.033	0.014	0.058
690-695	0.037	0.026	0.1
704-709	0.006	0.039	0.05
716-721	0.089	0.003	0.097
721-726	0.126	0	0.139
726-731	0.03	0.006	0.041
731-736	0.01	0.008	0.021
747-752	0.039	0.017	0.066
752-757	0.022	0.005	0.038
757-762	0.009	0.026	0.041
762-767	0.011	0.011	0.025
773-778	0.026	0.013	0.042
783-788	0.011	0.008	0.033
793-798	0.034	0.058	0.092
798-803	0.047	0.072	0.149
824-829	0.019	0.003	0.022
829-834	0.024	0.018	0.055
834-839	0.006	0.006	0.014
839-844	0.005	0.058	0.068
844-849	0.047	0.014	0.113
860-865	0.008	0.216	0.26
870-875	0	0.023	0.023
875-880	0.011	0.08	0.094
880-885	0.011	0.02	0.037
885-890	0.026	0	0.026
890-895	0.009	0	0.009
895-900	0.014	0.006	0.023
900-905	0.019	0.008	0.036
905-910	0.026	0.008	0.066
910-915	0.019	0.133	0.16
915-920	0.047	0.134	0.212

from North America (Dean et al. 1996) and elsewhere (Dean 2000). The ca. 3,400 BP phase/frequency shift (Figure 8) is also evident in both the herring and anchovy data (Figure 11). Palynological climate proxy records from sites around British Columbia record widespread and regionally variable climate change about that time, which correspond to the development of neoglacial conditions in the Cascadia region (Pellatt et al. 2001). Conditions on the west coast of Vancouver Island changed from warmer and dryer than at present to cooler and wetter than at present. A 120- to180-year cycle, in the Northern Anchovy data, between 1,800 and 3,000 yBP, appears to have been a temporary signal, while the 680-year cycle could be the anomalous result of three nearby samples with very high anchovy scale populations.

Analysis of the data using SA shows that there is also a positive cross-correlation at 0.0125 cpy (80-year period) between herring remains and the brighter diatom rich layers that were deposited under cold upwelling conditions at the Gleissberg Cycle frequency (Figure 11). Additional SA analysis (Figure 12) indicates that herring and anchovy have neither a positive nor negative correlation with each other at Gleissberg cycle frequencies. Squared coherency analysis also indicates that peaks in cross-amplitude spectrum and negative (–3 radians) correlation between herring and anchovy at the Gleissberg cycle band (70- to 90-

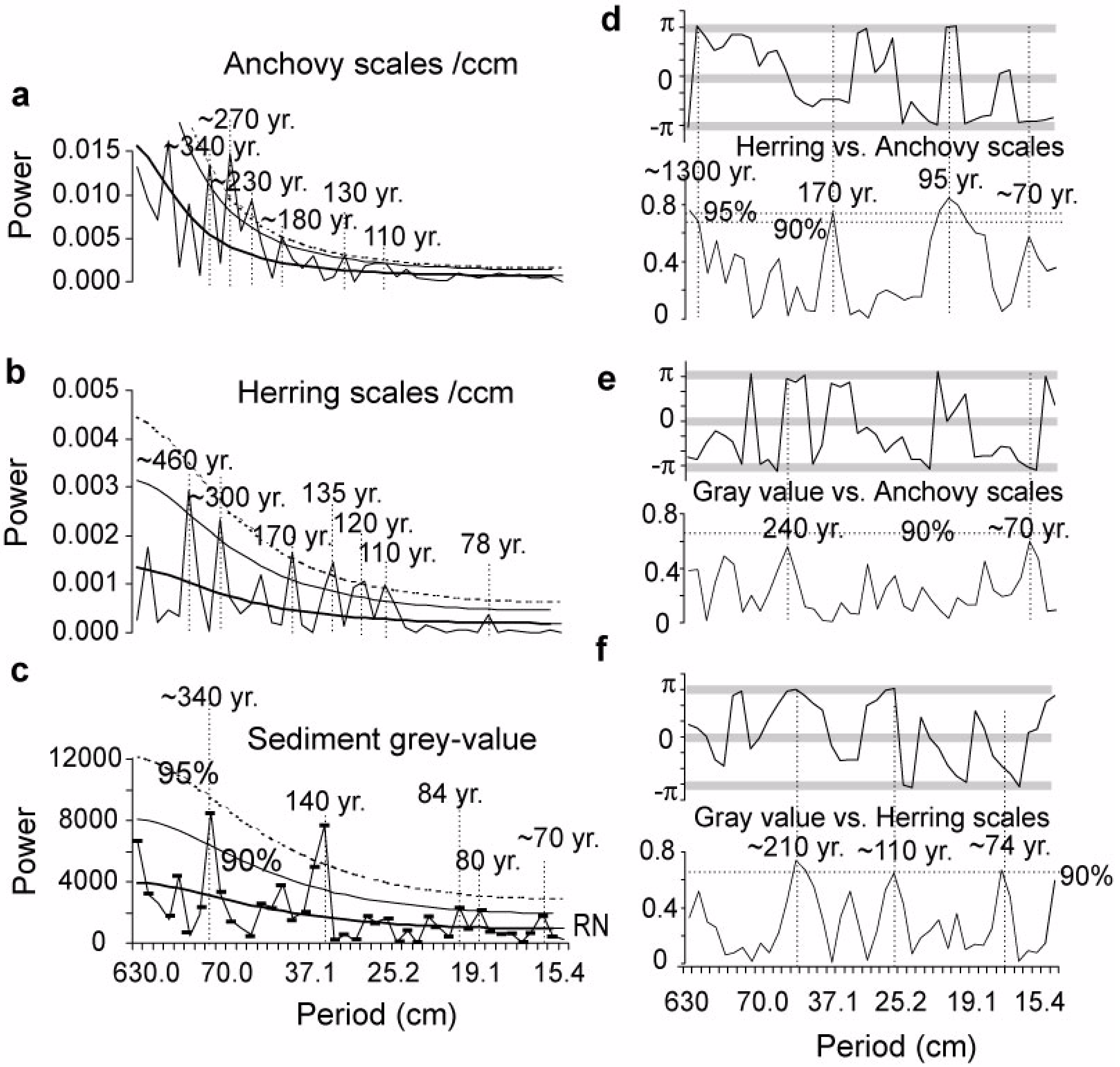

Figure 10. Spectral analysis periodograms with red noise levels (RN), as well as 90% and 95% non-randomness confidence levels (see text for details) for anchovy (**a**), herring (**b**), and sediment gray-scale value data (**c**), for the interval from 287-920 cm depth. Periods in years are based on a constant sedimentation rate of 0.23cm/year. Standard error for bandwidth of cycles due to standard error of ^{14}C data is ±7 percent. Black bars mark bandwidth error for each period. d-f: Cross-spectral analysis utilizing a 5-point-lag Hamming window for gray-scale value data with anchovy and herring scale abundances: squared coherency (bottom) and phase spectrum ($+\pi$ to $-\pi$) at top: horizontal gray bars mark in-phase (+) or inverse (–) cross-correlation. Dotted vertical lines mark periods that are cross-correlated. Dotted horizontal lines mark 90% and 95% confidence level (calculated from the F-distribution). Note that most of the significant periods in (**d**) have negatively cross-correlated amplitudes and are phase shifted (i.e., they are not directly correlated in time) except for the 56-57, 74, and 77 year periods. These intervals show an in-phase correlation between bright sediments and herring and a negative cross correlation (+/– π) between herring and anchovy and gray-scale values and anchovy. Note that the strong decrease in power with decreasing period is primarily the result of non-equidistant sampling with the fish data.

year wavelength, Figure 12) is not significant at the 95% confidence level calculated after Emery and Thomson (2001). There may be a correlation between herring and anchovy populations at higher frequencies (e.g., at time-scales of years to interdecadal scales; Chavez et al. 2003) but detection was not possible at the sampling resolution available here. Both species are negatively correlated with a 1,300-year cycle that we associate with the Bond cycle. The herring data is also positively correlated to the gray values for cycle periods of 210 and 300 years, whereas the anchovy are nega-

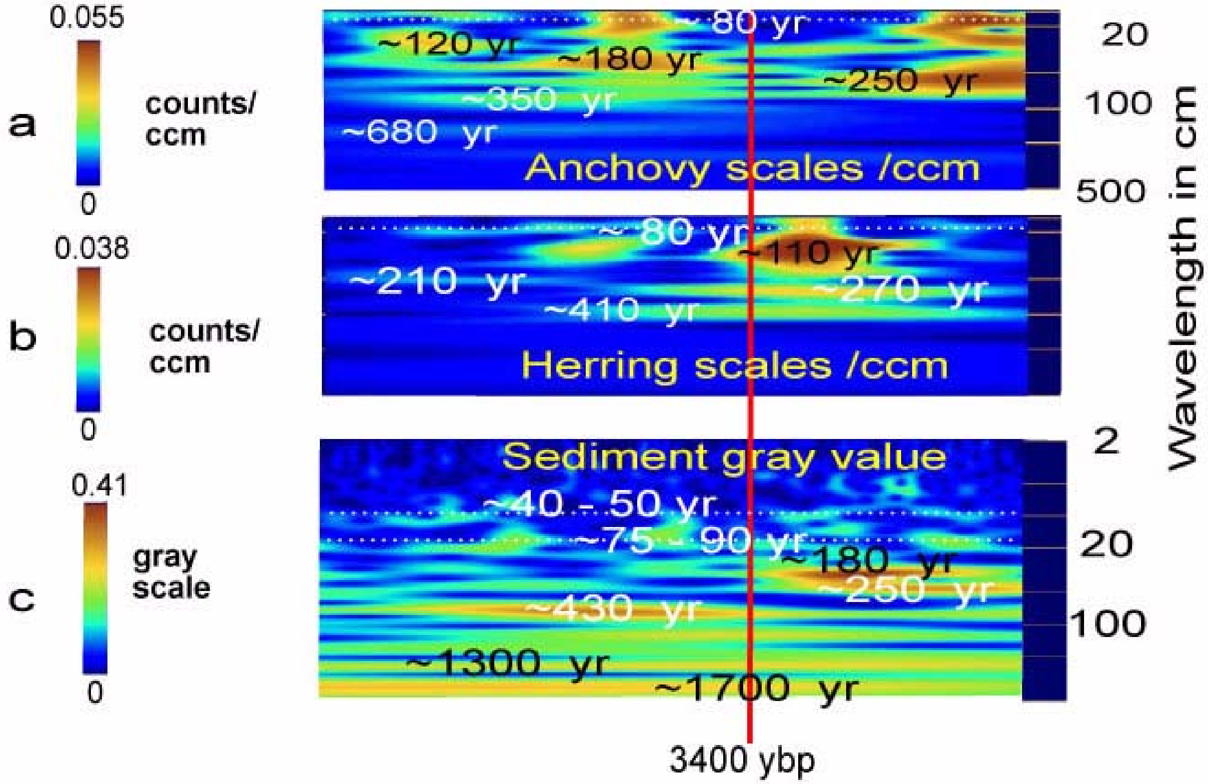

Figure 11 (a-c). Wavelet analyses for the predominantly well-laminated and densely fish-sampled core interval from 287-920 cm deposited between 1,800 and 4,500 years BP based on ^{14}C dates. Wavelet analysis of (**a, b**) different types of fish abundance data, from the absolute abundance of scales/cm^3, (**c**) gray-scale value x-ray image line scan data from sediment core. The duration for cycle lengths inside the wavelet scalograms are according to a mean sedimentation rate of 0.23 cm/yr. Color codes for Wavelet coefficients (in amplitudes of periodic cycles) on left sides of scalograms. Vertical red line marks an abrupt jump in the wavelet coefficients at ~720 cm (~3,400 years BP). Vertical scale for e-g is logarithmically scaled.

tively correlated to gray values at 340-year periods. Our findings indicate particularly close relationships between the Gleissberg solar cycle and the cyclicity of both fish species examined here, particularly Pacific Herring populations, and by inference ocean productivity. This relationship holds through most of the 1,800-4,700 years BP record even through a major climate shift at 3,400 years BP that disrupted most other cycles (Figure 11). Our findings compare favorably with the 100-year rate of anchovy fluctuation in Santa Barbara Basin between A.D. 270-1970 (Baumgartner et al. 1992) that falls within the variability of the Gleissberg Cycle (Garcia and Mouradian 1998). Because the anchovy populations of the North American CUD are linked, there is an indication that these pelagic fish species may have been fluctuating according to the Gleissberg Cycle through at least the last 4,700 years.

Correlation between solar activity and climate change has been suggested at a variety of different scales. Satellite-based measurements do show that there is a clear correlation between solar irradiance and the 11-year Schwabe cycle. Although the irradiance amplitude through the Schwabe cycle is only ~ 0.1% (Beer et al. 2000) this energy variability may be sufficient to produce changes in the surface climate as a result of atmospheric dynamic responses to changes in temperature and stratospheric ozone (Schindell et al. 1999; Haigh 2001) or perhaps due to changes in cloudiness caused by variations in the intensity of galactic cosmic rays in the atmosphere (Carslaw et al. 2002; Shaviv and Veizer 2003). There is also growing evidence that solar forcing, at longer time-scales, may be an important driving forces of the climate system (Soon et al. 2000; Beer et al. 2000) and dependent ecosystems at several temporal scales

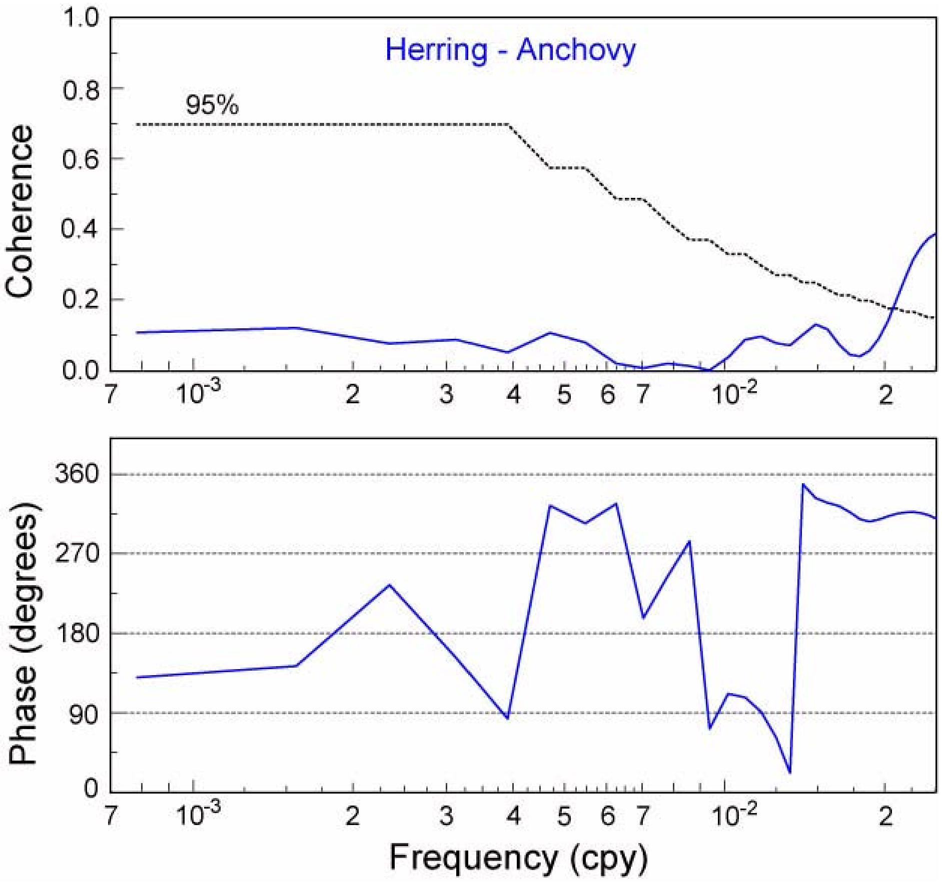

Figure 12. Squared coherency and 95% confidence level calculations between Northern Anchovy and Pacific Herring.

through the late Holocene (Haigh 2001; Bond et al. 2001; Schindell et al. 2001).

These examples of possible mechanisms for solar-driven climate change, and the teleconnection mechanisms proposed to propagate them globally, provide independent support for our hypothesis that solar forcing at the Gleissberg frequency seems to be an important control on the cycling of Pacific Herring and Northern Anchovy. However, solar forcing need not be the only mechanism involved. The observation that the solar irradiance driven Gleissberg cycle is unaffected by a major climate shift that disrupted several other cycles is in itself suggestive that there are at least two independent climate forcing mechanisms at play.

Our correlation analysis of the fish data indicates that the ecosystem in Effingham Inlet is varying according to the climatic changes recorded in the sediments, regardless of the ultimate source of the climate forcing. Population fluctuations such as those indicated in our data are inevitable as these ecosystem shifts affect the carrying capacity of the environment (Francis et al. 1999).

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