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Late Holocene variability in pelagic fish scales and dinoflagellate cysts along the west coast of Vancouver Island, NE Pacific Ocean

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Abstract

Fish stocks and dinoflagellates are essential components of the marine food chain. Sediment cores from a predominantly anoxic basin in Effingham Inlet, Vancouver Island, British Columbia, archive a late Holocene (~500–5300 years BP) record of paleoproductivity in the North American Coastal Upwelling Domain (CUD). We present evidence that late Holocene changes in the dinoflagellate cyst assemblages, sedimentary record, and fish stocks in the northeastern Pacific Ocean fluctuated, at least partially, in accordance with regional and global climate cycles.

Principal components analysis (PCA), and trend, wavelet and spectral analyses were used to identify relationships, cycles and trends in sediment grey-scale values, and the abundances of fish scales and dinoflagellate cysts on centennial to millennial time scales. Most observed cycles fluctuated in intensity over time, particularly following transition of the regional climate to a higher rainfall phase that impacted coastal oceanic dynamics ~3400 ± 150 years ago. Correlation of the marine paleoproductivity records observed in Effingham Inlet with solar influenced climate proxy cycles observed in the North Atlantic region indicates that solar forcing at different scales might have influenced the climate in the northeast Pacific as well. In particular an 1100- to 1400-year cycle in regional climate is well represented in the fish productivity proxy and sedimentological record. It was also observed that colder water, high-productivity, *Selenopemphix nephroides* and anchovy-dominated “Anchovy Regime” ecosystems alternate with warmer water, herring-dominated “Herring Regime” ecosystems at millennial time scales. The fish scale record preserved in Effingham Inlet indicates that the NE Pacific is now in transition from an ‘anchovy-’ to a ‘herring’-dominated regime.

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1. Introduction

Sub-decadal climate variability in the northeastern Pacific Ocean is affected by interdependent variability in the Aleutian Low (AL) and North Pacific High (NPH) pressure systems, the Jet Stream, and the equatorial El Niño/La Niña cycle (e.g., Chavez et al., 2003; Schwing et al., 2002; Ware and Thomson, 2000). 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). At present, the instrument record is too short for the identification of longer than decadal-scale climate cycles, which have been linked to

climate change events such as the well-publicized collapse of various west coast North American commercial fisheries (Hare et al., 1999). Because long-term trends in regional and global temperatures are difficult to resolve with relatively short historical records, a more complete understanding of medium and long-term climate oscillations and their linkages to short-term variations can only be achieved by turning to the geological record.

This research is based on a continuous sediment color record, derived from line-scans of X-ray positive images as well as counts of dinoflagellate cysts and fish scales from a ~1140-cm piston core taken from the inner basin of Effingham Inlet, Vancouver Island (Fig. 1). The mostly anoxic condition at the sediment–

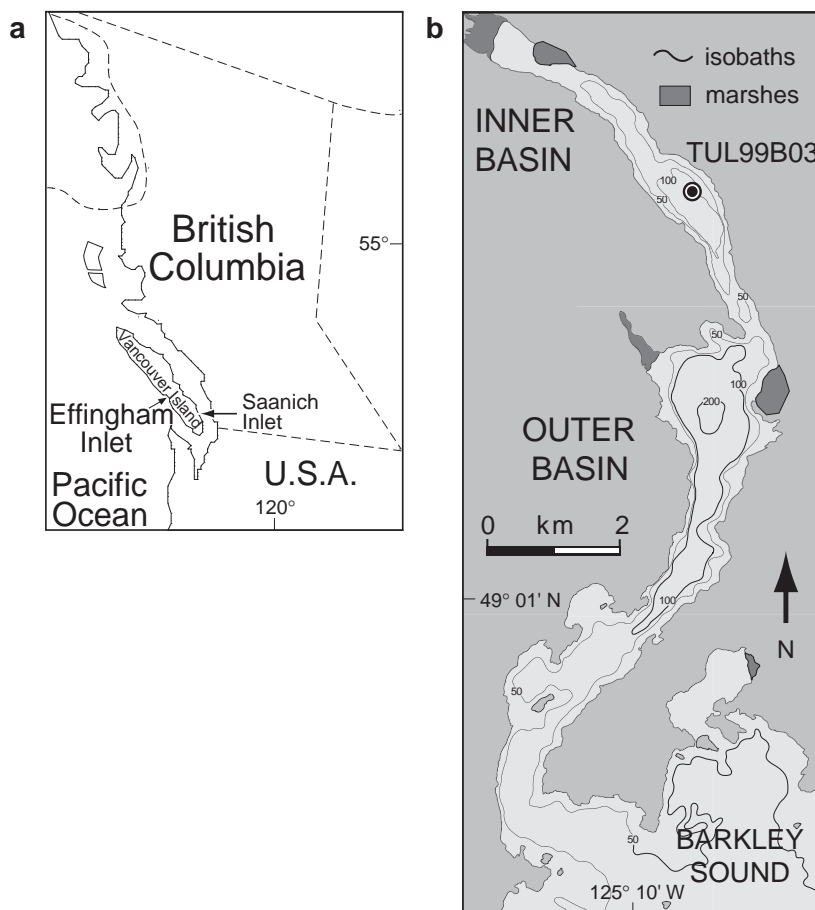


Fig. 1. (a) Location map of southern British Columbia including Vancouver Island. (b) Details of Effingham Inlet showing water depths and location of piston core TUL99B03 collected in the inner basin.

water interface that has characterized this basin through much of the Holocene has provided an excellent environment for the preservation of biotic debris raining down through the water column. The preservation of this material as annual laminae (varves) has permitted us to derive high-resolution estimates of changes in the rate of sedimentation and paleoproductivity.

The purpose of this study is to identify, quantify and determine possible causes of any variability in dinoflagellate cysts and pelagic fish productivity in a sedimentary record from the NE Pacific through the past ~5300 years. This study encompasses the complete sedimentary record of core TUL99B03 (~11.4 m; ~500–5300 years BP). In addition to presenting previously unpublished dinoflagellate cyst data, this study also summarizes and provides a correlation between the various biotic and sedimentary dynamics that have been active in Effingham Inlet through the Holocene. This research has also permitted detection and interpretation of statistically significant multi-centennial to millennial-scale trends and cycles in paleoproductivity, and NE Pacific climate.

1.1. Previous work

Previous research from several locations within Effingham Inlet has concentrated on understanding climate change variability in the region through analysis of several climate change proxies (e.g., cyclostratigraphy, sedimentology, dinoflagellates cysts, diatoms, foraminifera) archived in laminated Holocene-age sedimentary cores.

In a distributional study Patterson et al. (2000) delineated dysoxic/anoxic conditions in the Effingham Inlet complex utilizing foraminifera as proxies of oxygenation levels to recognize a whole range of subtle variations in paleoceanographic/atmospheric circulation.

Kumar and Patterson (2002) identified about 20 taxa of dinoflagellate cysts preserved in modern Effingham Inlet sediments. They determined that recognized assemblages were primarily controlled by the degree of oceanographic influence (nutrient supply and salinity) in the Inlet, and air or surface water temperature.

A series of studies (Chang et al., 2003; Patterson et al., 2004a,b) on core TUL99B03 from the inner

basin of Effingham Inlet focused on the nature and pattern of sedimentation in the Inlet as well as the paleoceanographic and climatic forcing factors that influence the abundance and temporal changes in phytoplankton and fish populations. For example, Chang et al. (2003) carried out detailed analysis of several 15- to 20-cm long well-laminated sections from core TUL99B03. They determined that seasonal fluctuation in diatom productivity controlled the thickness and color of the annual sediment laminations through the past ~500–5300 years. Thicker and brighter laminae are related to strong spring blooms and thinner, darker laminae are linked to reduced diatom productivity. This productivity record is overlain by fluctuations in clastic (mostly clay) sediment supply. Unfortunately, the spacing of the samples in that study precluded interpretation of continuous long-term paleoceanographic trends and cycles.

The study of Patterson et al. (2004a) focused on taxonomy, abundance and temporal changes in fish populations from ~1800 to ~4700 cal years BP in core TUL99B03. These results indicate that anchovy and herring populations cycle at decadal to centennial scales, with a particularly well-defined variability at the Gleissberg solar cycle (~80–90 years).

Patterson et al. (2004b) examined a well-laminated 7.8-m interval (~1440–4485 years BP) of core TUL99B03. They compared line-scans of X-ray image grey-values with several global and regional climate cycles, including the cosmogenic nuclide ^{14}C record of Stuiver et al. (1998; with consideration of the stratigraphic adjustments made by Bond et al., 2001). They recognized evidence of a strong cooling at ~3550 years BP in the NE Pacific and delineated multi-centennial sedimentary cycles that they linked to a weakening of high-frequency solar fluctuations. Three episodes of low solar activity at ~2350, 2750 and ~3350 years BP were correlated to intervals of thick, clay-rich sedimentation, indicating wet conditions along the NE Pacific coast. These intervals of higher precipitation levels are tentatively correlated to regional intensification of the AL caused by eastward movement of the Center of Action (COA) of the AL, which occurs during solar minima (Christoforou and Hameed, 1997; Hameed and Lee, 2003).

1.2. Current climatic–oceanographic conditions along the NE Pacific coast

Changes in productivity in Effingham Inlet can be linked to variations in the relative thickness of layers of seasonally deposited diatomaceous-ooze and terrigenous material. Lighter colored laminations deposited during the spring to fall are composed primarily of skeletal remains of diatoms and other phytoplankton while laminations deposited during the rainier winter months when marine productivity is low are primarily made up of detrital terrigenous grains that are washed into the Inlet from the nearby shore (Chang et al., 2003). These laminated deposits can, in turn, be linked to changing ocean climate conditions (McQuoid and Hobson, 2001). Seasonally dependent upwelling (caused by NPH wind-driven Ekman transport of surface waters away from the Vancouver Island continental margin, usually between May and August at present) is the principal mechanism providing nutrients to the coastal ocean off southwest British Columbia (Thomson and Gower, 1998). Over time, changing climatic conditions impact the AL and NPH, leading to shifts in surface wind stress, mixed layer depth, and stratification. These changes also modify the temperature, salinity and nutrient content of the surface layer of the ocean where phytoplankton growth is concentrated (Brodeur and Ware, 1992) and are the primary drivers of cyclical changes in primary production, impacting the floral makeup, as well as the timing and intensity of phytoplankton blooms (Ware and Thomson, 1991).

The phytoplankton in this region consists primarily of diatoms with lesser but significant populations of dinoflagellates. As with the diatoms, variations in the populations of dinoflagellates reflect local productivity changes. Dinoflagellate cyst abundance is a direct indicator of marine productivity while the percentages of different dinoflagellate cyst species indicate differences in salinity, sea surface temperature (SST), and nutrient supply (Kumar and Patterson, 2002). In contrast, fish are nektonic organisms whose populations reflect more broadly the environmental conditions in the NE Pacific. Since pelagic fish respond to food availability, these changes cascade through the various trophic levels eventually impacting commercially important pelagic fish populations throughout the region.

1.3. Pacific herring and northern anchovy ecology in the NE Pacific

Pacific herring (*Clupea harengus pallasii* Valenciennes, 1847) and northern anchovy (*Engraulis mordax mordax* Girard, 1854) are two particularly abundant taxa in the Holocene sediments of Effingham Inlet (Patterson et al., 2004a). These species have previously been demonstrated to be sensitive to changes in water mass, surface productivity, ocean currents, as well as indicators of temporal variability in overall fish stocks and paleoproductivity (e.g., Beamish, 1993; Chavez et al., 2003). Both Pacific herring and northern anchovy undergo significant population fluctuations over time. However, because of the brief modern fishing records, the frequency and amplitude of the fluctuations are largely unknown (Holmgren-Urba and Baumgartner, 1993; Schweigert, 1995; Tunnicliffe et al., 2001). Pacific herring is relatively cosmopolitan and has preferentially been found together with sardines along the west coast of North America (Beamish, 1993). Sardines and herring occur along Vancouver Island during summers when there are sustained periods of northerly winds (Hsieh et al., 1995). ‘Sardine regime’ type conditions in the region are most common during ‘Eastern Pacific Warm Phases’ (Chavez et al., 2003) such as occurred between 1977 and 1998. Herring was particularly common in Canadian waters during 1977; an anomalously warm year (e.g., Beamish, 1993; Hollowed and Wooster, 1995).

In contrast, the northern anchovy is typically at the northern limit of its range in British Columbia. Anchovy are more productive in this region during cooler periods (e.g., 1965–1976) when AL influence was diminished, but coastal upwelling was intensified, such as occurs during ‘Eastern Pacific Cool Phases’ (e.g., Chavez et al., 2003).

2. Data and material

2.1. Sedimentary data

An 11.4-m long 10-cm diameter piston core was collected from the center of the inner basin in Effingham Inlet, west coast of Vancouver Island, Canada (49°20.50'N, 125°30.54'W, at a water depth

of ~120 m) (Fig. 1) on a cruise by the research vessel *CCGS John P. Tully* in October 1999. Sediment recovery from the core was almost complete (~97%). These sediments predominantly consisted of a mixture of unconsolidated brown mud and diatom ooze. Approximately 80% of the recovered sediment core was composed of laminated sediments, massive units comprised ~18% of the core and ~2% of the core consisted of distorted laminae and graded beds. Most of the laminated sediments occurred between ~145 and 920 cm in the core. These laminae are composed of couplets of dark, mineral-rich autumn–winter layers and bright, diatom-rich spring–summer layers altogether representing distinct annual sedimentary cycles (Chang et al., 2003). The couplet thickness ranges from 0.15 to 0.8 cm. The upper ~145 cm and bottom ~110 cm of the core are characterized by long core intervals (>20 cm) without laminations, and the presence of significant slumping related material that disrupted the laminations. X-ray positive images were scanned at 256 grey-scale resolutions to generate a 130,787 pixel long and three pixels wide line-scan of the core (116 pixels=1 cm). Due to lost core segments, and poor image quality in places, approximately 12% of the image data had to be linearly interpolated. A complete description of the sedimentology of core TUL99B03, including a detailed description of the methodology used for extracting the grey-scale value and lamination thickness data from X-ray image line-scans is presented in Patterson et al. (2004b).

Thickness measurements of annual laminae (Patterson et al., 2004b) and accurate ^{14}C ages (Table 1) indicate that the sedimentation rate averaged over 1 m was relatively consistent at ~0.25 cm/year through the lower ~9.5 m of core, decreasing to ~0.15–0.2 cm/year in the upper ~1.8 m of the core. However, ab-

solute variation in lamination thickness of between 0.15 and 0.8 cm over intervals of less than 5 cm indicates significant short-term fluctuations in the sedimentation rate that vary by up to a factor of 5 (Patterson et al., 2004b). Correlation with other cores (Dallimore, 2001) suggest that the last ~500 years was not recovered in this core due to over-penetration of the piston corer. The calibrated marine shell dates were not used in construction of the age model as the marine reservoir effect of 120 ± 45 years (see Table 1) is still disputed for restricted fjords environments such as Effingham Inlet (R. Beukens, personal communication, 2002). Our age model (Patterson et al., 2004b) is primarily based on laminae couplet thickness in the interval from ~1400 to 4600 years BP. The relative ages of this interval are tied to three twig/wood radiocarbon ages that are calibrated using INTCAL98 (Stuiver et al., 1998) and linearly extrapolated to accommodate the mostly non-laminated uppermost and lowermost parts of the section (Fig. 2).

2.2. Palynomorphs

Dinoflagellate cysts, spores and pollen counts were carried out on 48 almost equidistantly spaced 1-cm thick subsamples throughout core TUL99B03 (~24 cm=~96 years sampling interval; Fig. 3). Sediment samples used for dinoflagellate cyst analysis were filtered through both 1-mm and 100- μm sieves respectively to remove coarser material, and to separate finer sediments. The finer sediments (<100 μm) were chemically macerated for preparation of palynological slides using the following method:

1. Volume and weight of each sample were determined by putting samples in a calibrated cylinder.

Table 1
 ^{14}C dates in core TUL99B03 (Effingham inlet)

Sample number	Dated material	Lithology	Isotrace number (U. Toronto)	Depth in core (cm)	^{14}C year BP	^{14}C CAL year BP
RC03S201	Bivalve shell 88 mg	Laminated	TO-8672	169	1770 ± 60	1495 ± 160^a
RC03S301	Twig 135 mg	Laminated	TO-8673	286	2050 ± 70	1858 ± 62
RC03S501	Twig 545 mg	Laminated	TO-8674	553	2830 ± 60	2980 ± 150
RC03S601	Shell fragments 355 mg	Laminated	TO-8675	822	3890 ± 80	4085 ± 245^a
RC03S701	Wood 562 mg	Massive	TO-8676	937	4190 ± 80	4745 ± 175

^a Inlet water residence time of CAL (120 ± 45 years), calculated from a wood/bivalve pair at 937/900 cm from core TUL99B11 (Effingham Inlet, outer basin).

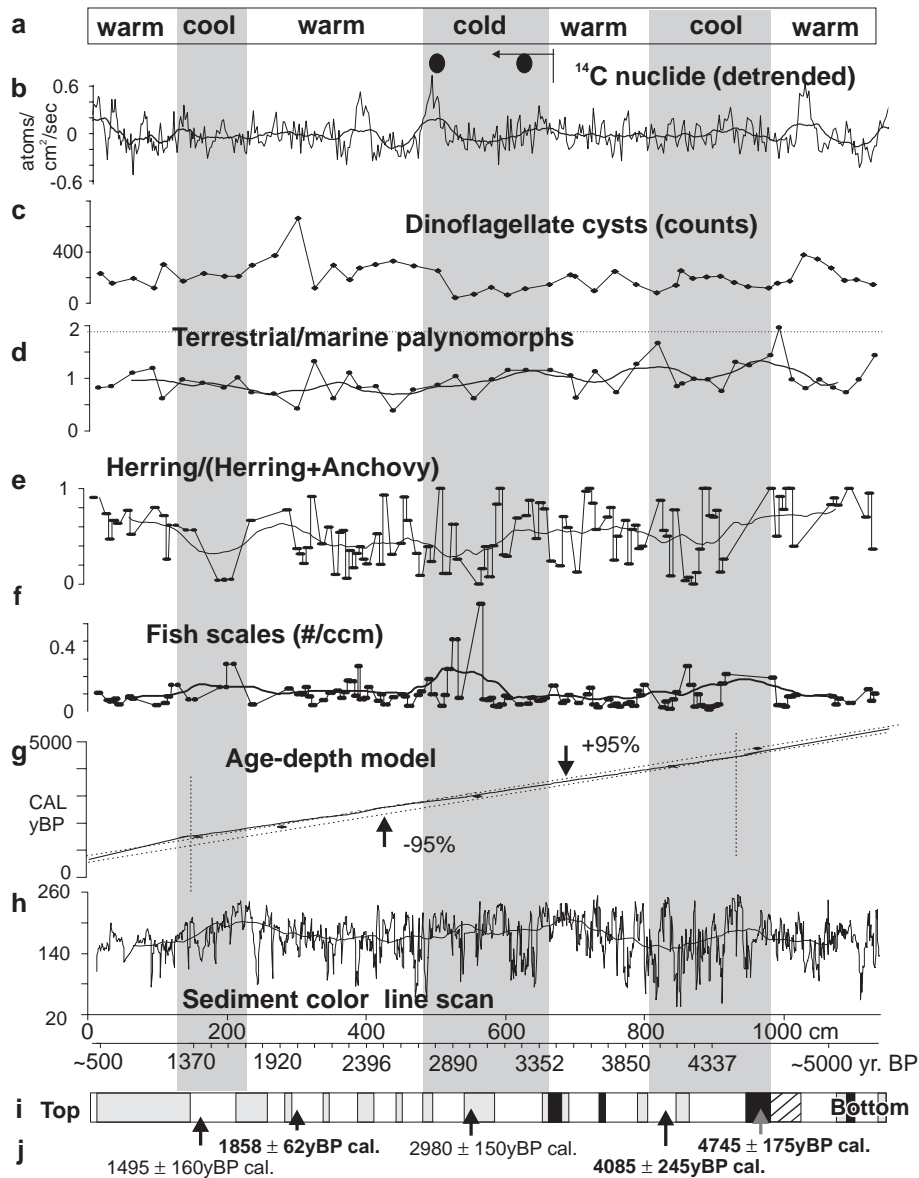


Fig. 2. Major palynomorph, fish scale, age–depth model (after Patterson et al., 2004b) and sedimentary time series data of piston core TUL99B03, Effingham inlet, West coast Vancouver Island. (a) Global temperature stages derived from drift-ice debris records (Bond et al., 2001); black ellipses—major Rocky Mountain glacier advances (~3300 and 2800 years BP), line with arrow—vegetation shift at ~3460 years BP and (Pellatt and Mathewes, 1997); (b) detrended ^{14}C cosmogenic nuclide in 10-year time steps and 200-year moving average (Bond et al., 2001); (c) dinoflagellate cyst counts, core TUL99B03; (d) terrestrial/marine palynomorph ratio for core TUL99B03 with 5 cm/1 m moving average; dotted line marks present ratio at the core location (Kumar and Patterson, 2002); (e) herring/(herring+anchovy) ratio TUL99B03 with 2-m moving average; (f) fish scale counts (#/cm³) from core TUL99B03 with 2-m moving average. Note that fish and palynomorph samples are non-equidistant; (g) age–depth model, crosses mark shell ages, dots marks wood ages, tilted dotted lines mark 95% confidence interval of trend-line from calibrated ^{14}C wood ages, vertical dotted lines mark refined age model (~10-year intervals) from varve thickness measurements (middle) and extrapolated ages (no continuous lamination) on right and left (bottom and top of core), for details see text; (h) sediment color in grey-scale (0—black, 255—white) derived from X-ray line scans of core surface with depth-scale (equidistant) and time-scale (non-equidistant); (i) general lithology: white—>80% laminated mud, grey—<80% laminated mud, black—non-laminated mud, striped—distorted sedimentation; vertical grey bands highlights ‘cool’ intervals after Bond et al., 2001; (j) calibrated ^{14}C ages (see Table 1).

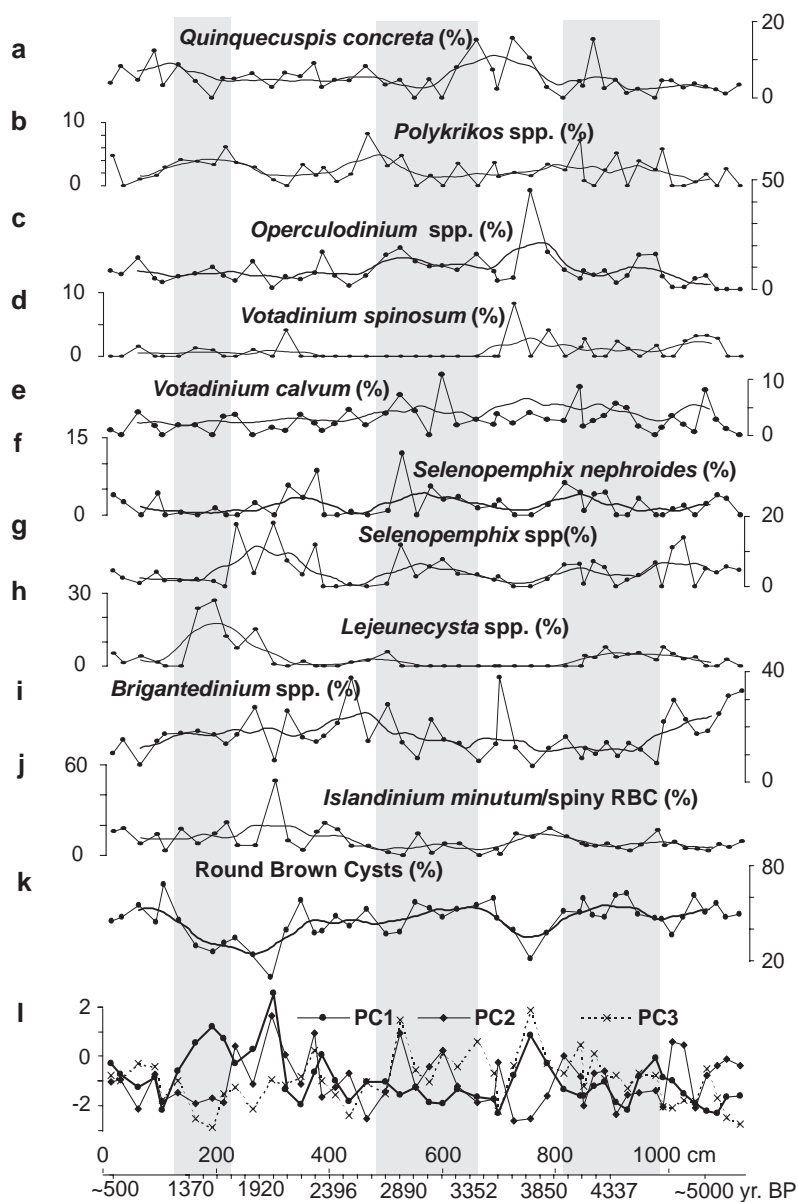


Fig. 3. (a–k) Major palynomorph time series data of core TUL99B03 with 5 cm/1 m moving average, Effingham inlet, l: scores of principal components (PCs) from dinoflagellate cyst percentages (a–k). Vertical grey bands mark ‘cool’ and ‘cold’ intervals after Bond et al. (2001).

2. Samples were sieved through a 10- μ m sieve to filter out clay minerals.
3. Samples were chemically treated with 10% HCL (four times) alternating with HF (three times) with the last HF treatment being left overnight. Following each chemical treatment, samples were heated

for 20 min in a dry bath, followed by 10 min of centrifuging. The processed samples were then washed with distilled water.

4. The washed residues were once again filtered through a 10- μ m sieve several times until the filtered water became clear.

5. One drop of the resultant residue was mounted in gelatin without any coloring and two slides from each sample were prepared for analysis.

Species identification was primarily based on Rochon et al. (1999). Each slide was thoroughly scanned for rare species before counting, and ten complete transacts were counted at $\times 400$ magnification from each slide. The counts included dinoflagellate cyst species, dinoflagellate cyst morphotypes, pollen grains and spores. It was not always possible to identify dinoflagellate cysts to species level because of poor preservation and lack of taxonomic data on the Holocene dinoflagellate cysts from the Pacific coast of Canada. Thus several cysts were grouped into various dinoflagellate cyst morphotypes.

Relative abundance (i.e., percentages) of each dinoflagellate cysts and morphotypes from the total dinoflagellate cyst counts were calculated (Appendix A). The total sum of pollen and spores is presented as terrestrial palynomorphs and total dinoflagellate cyst counts as marine palynomorphs. Statistical analysis was carried out on the relative abundance data because of its independence from short-term fluctuations in terrestrial sediment supply.

2.3. Fish scale data

Fish scales were well preserved in these sediments and abundances were recorded as the number of scales/cm³ of sediment in 114 subsamples from core TUL99B03. The complete data set of fish scales from 10 species, as well as fish bone fragment counts, and sample preparation methodology is found in Patterson et al. (2004a). To avoid over counting of fragmented specimens, only scales with intact focal points were included in the study. Most samples were taken at 2- to 10-cm intervals, although there were nine sampling intervals where spacing ranged between 20 and 62 cm. The average fish scale-sampling interval was 9.8 cm. This study focuses on northern Anchovy and Pacific herring scale counts because of their sensitivity to environmental change (e.g., Beamish, 1993; Chavez et al., 2003). In addition, we use the herring/(anchovy+herring) ratio as a sedimentation rate independent proxy for paleoenvironmental change. The complete fish scale and dinoflagellate cyst data sets derived

from core TUL99B03 are available at <http://www.carleton.ca/ccrg>.

3. Mathematical–statistical methods

3.1. Method selection criteria and sampling intervals in depth and time

We applied continuous wavelet analysis transform (CWT), spectral analysis (SA), and cross-spectral analysis (CSA) to our data sets in order to determine and quantify the trends and cycles, as well as any bandwidth-dependent relations between the different time series. We performed principal components analysis (PCA) on the relative frequencies of the dinoflagellate cyst counts to determine relationships between species and their possible environmental control.

We focused on trends and cycles in dinoflagellate cyst species data and their relation to other paleo-environmental proxies. The results of a high-resolution time series analysis on the fish data from ~1440 years BP to ~4600 years BP in core TUL99B03 is fully documented in Patterson et al. (2004a). Correlation between sediment grey-scale value data from TUL99B03 and ¹⁴C cosmogenic production rates is discussed in Patterson et al. (2004b).

We used the percentages of dinoflagellate cyst taxa present rather than cyst counts for the time series analyses to remove bias due to fluctuating sediment dilution. The originally non-equidistantly spaced data were transformed into equidistant 5-cm intervals by linear interpolation using the MITTEL.N.C software package (available at www.geocities.com/speedstat). For spectral analysis, the analysed interval ranges from 16.5 cm (uppermost dinoflagellate cyst sample) to 1126.5 cm (lowermost dinoflagellate cyst sample). However, we only graphically displayed and interpreted results of time series analysis of dinoflagellate cyst data for cycle lengths of >50 cm, as the mean spacing between the dinoflagellate cyst samples is ~23 cm. We transformed the cycle lengths (*s*) into cycle duration (*t*) utilizing an average sedimentation rate of 0.25 cm/year, which was derived from the gradient of the trend line between 160 and 930 cm (Fig. 2g). This was an appropriate methodology because sedimentation rate fluctuations in section

TUL99B03 are mostly smoothed out over ~50-cm depth intervals (Patterson et al., 2004b) and are of low significance in the study of fluctuations of wavelengths longer than 50 cm (~200 years) resulting in the relationship:

$$t = s / (0.25 \text{ cm/year}).$$

3.2. Principal components analysis (PCA)

Principal components analysis is a multivariate method that linearly transforms the correlation matrix of independent variables (e.g., fossil taxa) into a principal component (PC) matrix according to linearly independent (=orthogonal) eigenvalues. We carried out a PCA without PC rotation using commercially available SPSS software. PCA has previously been widely used in geological and climatology studies (e.g., Von Storch et al., 2004) and in this study allows for the grouping and interpretation of dinoflagellate cyst count according to the correlations between species (“loadings”) and with the new PCs. Here, we utilized PCA to (1) to combine dinoflagellate cyst taxa into PC time series that are environmentally meaningful, and (2) to extract new environmental proxies.

3.3. Spectral analysis (SA) and cross spectral analysis (CSA)

Spectral analysis and CSA have been performed on selected dinoflagellate cyst species and fish species percentages. SA provides estimates of the “power” (signal variance per unit frequency band) as a function of frequency (Davis, 1986). The selection criteria were environmental sensitivity and occurrence of at least two specimens in all samples.

For SA, we calculated the periodograms of the Discrete Fourier transform from the equidistant data using the SPSS software, and calculated the red noise level from the lag-one autocorrelation coefficient according to Mann and Lees (1996) and the 90 and 95% red noise levels according to Prokoph et al. (2000).

Cross-spectral analysis with a 5-frequency Hamming Window was carried out using the SPSS software. This methodology has been used to identify the correlation between the different equidistant time series at specific bandwidths (=cycle lengths). Perio-

dicities with squared coherencies (~correlation coefficients) with a >95% confidence at 6 degrees of freedom (DOFs) per band (Torrence and Compo, 1998) are highlighted in the cross-spectrograms.

3.4. Continuous wavelet transform (CWT)

Continuous wavelet transform analysis of time series permits detection of cyclic signals not only according to their frequency, as with SA, but also permits simultaneous recognition of their absolute location and duration in core depth or time. The shape of the analyzing function is not necessarily trigonometric as with the Fourier transform, but can have different shapes that can be useful for different signal analysis purposes (e.g., Rioul and Vetterli, 1991). An adjustable parameter l for analysing window size provides enhanced resolution either in favour of frequency or time/depth.

We used the Morlet wavelet (Grossman and Morlet, 1984) as an analysis function with a window size of $l=10$ (i.e., 10 cycles per window) as it provides particularly good results for detection of periodic cycles in climate time series (Ware and Thomson, 2000). The wavelet coefficients in the time–frequency space are graphically represented as a “scalogram” with amplitudes of periodic signals coded in white, two shades of grey, and black. This type of wavelet transform has also been used for data from TUL99B03 and is described in detail in Patterson et al. (2004b). The software CWT.F utilized in the analysis is described in detail in Prokoph and Barthelmes (1996).

4. Results

4.1. Late Holocene occurrence and ecology of *palynomorphs* in core TUL99B03

The dinoflagellate cyst floras derived from the late Holocene sediments in core TUL99B03 are similar to those found at present within Effingham Inlet (Kumar and Patterson, 2002), but with some distinct differences. The present-day assemblage is comprised of 20 taxa, while only 11 taxa were identified through the 500–5300 years BP depositional interval in core TUL99B03 (Fig. 3, Appendix A). The lower diversity

observed in the core is the result of poorer preservation than in surface water samples and the resultant necessity to lump several taxa together.

Four taxa could be identified at the species level in the core; (*Quinquecuspis concreta* (Reid, 1977), *Votadinium spinosum* Reid, 1977, *Votadinium calvum* Reid, 1977, and *Selenopemphix nephroides* Benedek, 1972). It was not always possible to differentiate between *Islandinium minutum* Harland and Reid, 1980, *Islandinium?* var. *cesare*, *Pheopolykrikos hartmanii* Matsuoka and Fukuyo (1986) and *Echinidium karaense* Head et al. (2001), because the nature of the taxonomically important archaephyll shape and process morphology could not always be exactly discerned. For counting purposes, all such morphotypes were lumped together and identified as *I. minutum*/spiny round brown cysts. The difficulties encountered in distinguishing these taxa are not unprecedented. For example, De Vernal et al. (2001) had similar problems in separating these three morphologically similar spiny, spherical, brown cysts in samples from Arctic waters. Poor preservation of some cysts restricted identification of several taxa and morphotypes to the genus level; for example, species of *Polykrikos* Bütschli, 1873, *Operculodinium* (Deflandre and Cookson, 1955), *Selenopemphix* Benedek, 1972, *Lejeunecysta* (Reid, 1977). All spherical brown protoperidinioid cysts showing an opening were grouped together as *Brigantedinium* spp. Wall (1965), because the shape of the archaephyll could not be discerned. All spherical brown protoperidinioid cysts without any visible opening were lumped together as round brown cysts (RBC). A detailed taxonomic study of the Holocene dinoflagellate cysts from the Pacific coast of Canada is in progress.

RBCs were the most common taxa identified varying in abundance from between 10%–68% of the entire population, followed by *Islandinium minutum*/spiny round brown cysts (0–50%), *Operculodinium* spp. (0–45%), and *Brigantedinium* spp. (0–40%). The other taxa ranged in abundance from between 0 to 28% of the entire population (Fig. 3, Appendix A).

The terrestrial (pollen and spores) to marine palynomorph (dinoflagellate cysts) ratio ranged from 0.38 to 1.96 (Appendix A, Fig. 2d). Most samples, in particular those between 14 cm and ~750 cm depth (~500–3800 years BP), had an approximately equal

proportion (1:1) of terrestrial and marine palynomorphs. This palynomorph distribution is typical of the deeper and more saline outer basin of present-day Effingham Inlet (Kumar and Patterson, 2002). Below the 750-cm (~3800 years BP) horizon the marine/terrestrial palynomorph ratio increased to ~2:1. T/M values derived from present-day dinoflagellate cyst floras recovered from the inner basin of Effingham Inlet, ranged from 1.8:1 to 26:1 (Kumar and Patterson, 2002). There is no clear explanation at present for lower T/M ratio observed in the core compared to present day ratios. A change through the last ~500 years to a more restricted flow of water across the sill separating the inner and outer basins would provide one possible explanation for more terrestrial material being trapped and subsequently deposited in the basin at present. However, there is no compelling geologic or paleoceanographic evidence of either tectonic uplift or significant lowering of relative sea level in this time frame. There is also no indication that there has been any dramatic increase in precipitation to the area that would result in an increase in river discharged sediment bed load into the inner basin of Effingham Inlet.

4.2. Principal component analysis (PCA)

A PCA of the first three PCs derived from the percentage abundance of dinoflagellate cyst species (Fig. 3f) accounted for almost 50% of the total observed variance (Table 2). However, none of the PCs has a significant linear correlation with sedimentary parameters, fish scales and palynomorph proxies (Table 2).

Principal Component 1 combines *Islandinium minutum*/spiny with the inverse variability of round brown cysts (RBC). We interpret this PC as a ‘cold-water proxy’ because *I. minutum*/spiny round brown cysts occurs in high percentages in cold water <8 °C (Rochon et al., 1999). RBCs occur through a wider temperature range and are often associated with coastal upwelling events in Effingham Inlet (Kumar and Patterson, 2002). Principal Component 1 scores plot negatively during a ‘cold’ depositional episode (Patterson et al., 2004a,b) from the 470- to 660-cm (~2650 ± 130 years BP to ~3400 ± 130 years BP) interval in the core when PC3 (see below) predominated (Figs. 3f, 4a).

Table 2
PCA statistics

	Loadings (linear correlation coefficients)			Eigen value	% Variance	
	PC1	PC2	PC3			
<i>I. minutum</i> /Spiny RBC (%)	0.76	0.2	0.03	PC1	1.95	17.7
<i>Brigantedinium</i> spp. (%)	−0.3	0.31	−0.7	PC2	1.69	15.4
<i>Selenopemphix</i> spp. (%)	0.16	0.87	0.14	PC3	1.65	15
<i>S. nephroides</i> (%)	−0.23	0.57	0.4			
<i>Polykrikos</i> spp. (%)	0.2	−0.31	0.06			
Round brown cysts (%)	−0.84	−0.29	0.01			
<i>Operculodinium</i> (%)	0.3	−0.32	0.61			
<i>Lejeunecysta</i> spp. (%)	0.48	−0.22	−0.48			
<i>Votadinium calvum</i> (%)	−0.32	0.16	0.45			
<i>Votadinium spinosum</i> (%)	−0.1	−0.25	0.01			
<i>Quinquecuspis concreta</i> (%)	0.05	−0.22	0.42			
Passive parameters						
Sediment color (X-ray gray value)	0.11	−0.12	0.06			
Herring (#/ccm)	0.07	−0.09	−0.18			
Anchovy (#/ccm)	0.00	0.06	0.05			
Herring/(Herring+Anchovy)	0.05	0.01	−0.18			
Terrestrial/marine palynomorph	−0.10	−0.09	0.10			

Principal Component 2 is predominantly associated with the abundance of *Selenopemphix* taxa. *Selenopemphix nephroides* occurs preferentially under conditions of higher salinity (35–36‰) and warmer water (summer temperatures between 12 and 21 °C; Rochon et al., 1999). Species of *Selenopemphix* can thus be sensitive to both temperature and salinity (Rochon et al., 1999). However, we interpret this PC as a primarily ‘salinity proxy’ because at present *S. nephroides* is rare (0–3%) in lower salinity waters (27–32.5‰) of the inner basin (Kumar and Patterson, 2002). An observed percentage occurrence of up to 12% (i.e., PC2=1.92 at 527 cm

depth=~2900 years BP) of this species in TUL99B03 indicates that the surface water salinity during some parts of the late Holocene was significantly higher (>35‰) than at present in both the inner and outer basin (26–32‰). *Selenopemphix nephroides* Radi and de Vernal (2004) also interpret the presence of high proportions of *Selenopemphix* spp. as indicative of higher productivity.

Principal Component 3 is characterized by a negative correlation with the variability of *Brigantedinium* spp. and a positive correlation to *Operculodinium* spp. (Table 2). Interpretation of the ecological preference of both taxa is controversial but they are

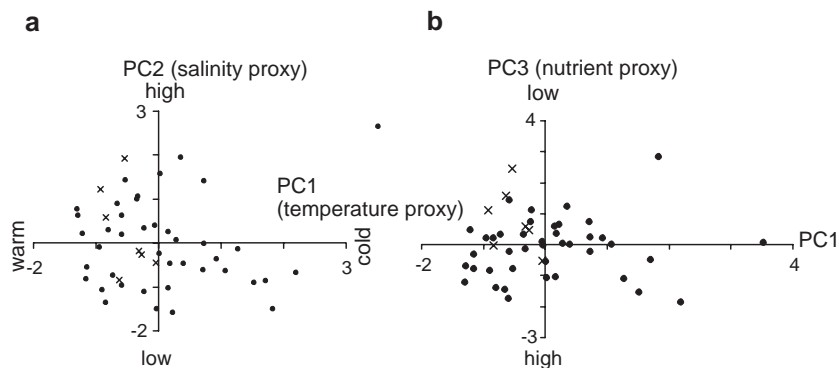


Fig. 4. Cross-plot of principal components of dinoflagellate samples of core TUL99B03; crosses: samples from 470–680 cm depth (‘cold’ interval), circles—all other samples. Note that most of the ‘cold’ interval samples plot into the low PC1 and high PC3 quadrant.

most often considered to be opportunistic (e.g., Rochon et al., 1999). Because *Brigantedinium* spp. is a P cyst and *Operculodinium* spp. is a G cyst differential preservation may also play an important role in explaining the strong negative correlation between the percentage occurrences of these two species. *Brigantedinium* spp. is heterotrophic, and typical of cold-water conditions, particularly in near-shore areas influenced by seasonal upwelling in coastal British Columbia (Radi and de Vernal, 2004). It is thus a proxy for primary productivity (e.g., Mudie et al., 1990; Rochon et al., 1999). At present, the

percentage of *Operculodinium* spp. is higher in the less saline, nutrient-depleted inner basin than in the more nutrient-rich outer basin where upwelled waters penetrate more frequently (Kumar and Patterson, 2002). They are particularly abundant in the inner basin in laminae associated with the fall season (Chang et al., 2003). *Brigantedinium* spp. is rare everywhere in the Effingham Inlet complex (Kumar and Patterson, 2002). Thus, we consider PC3 to be a ‘low nutrient proxy,’ which was particularly important during the $\sim 2650 \pm 130$ years BP to $\sim 3400 \pm 130$ years BP ‘cold’ episode (crosses in Fig. 4b).

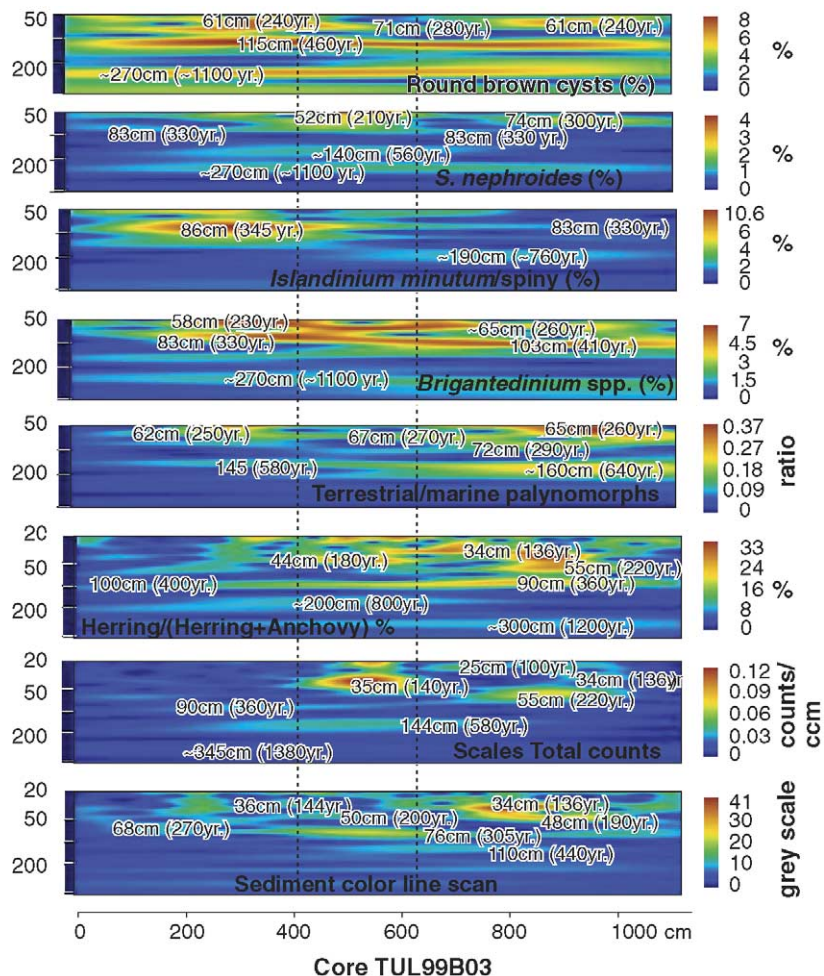


Fig. 5. Wavelet scalograms with cycle lengths (in length and time-scale according to a average sedimentation rate of 0.25 cm/year) of sedimentary, fish scale and dinoflagellate cyst time series of core TUL99B03. Dashed lines separate intervals of different cyclicity in sets (on top); right side—scales for wavelet coefficient (calibrated into amplitudes of sine waves). Left side—scale of 100 logarithmically spaced wavelength for a range 50–1000 cm for dinoflagellate data and 20–1000 cm for fish and sediment data.

4.3. Biological and sedimentary trends and cycles

Most of the sedimentary and biotic signals do not show any long-term linear trends through the 500- to 5300-year BP interval studied (Figs. 2,3) although cyclic distributional patterns abound. An exception is the terrestrial vs. marine palynomorph (T/M) ratio, which slightly decreases in younger sediments (Fig. 2). The decreasing T/M ratio trend from ~5000 to 500 years BP could represent a gradual increase in the preservation of marine palynomorphs, because

more disturbed sedimentation after earthquakes before ~4000 years BP (Patterson et al., 2004b) may have preferentially destroyed the more fragile palynomorphs.

Most time series do show both distinctly negative (e.g., herring/(herring+anchovy) ratio [H/A], *Islandinium minutum*/spiny round brown cysts percentage), and positive excursions (e.g., fish scales/ccm, sediment color, ‘round brown cysts’ percentage) during the $\sim 2650 \pm 130$ years BP to $\sim 3400 \pm 130$ years BP cold episode (Figs. 2,3).

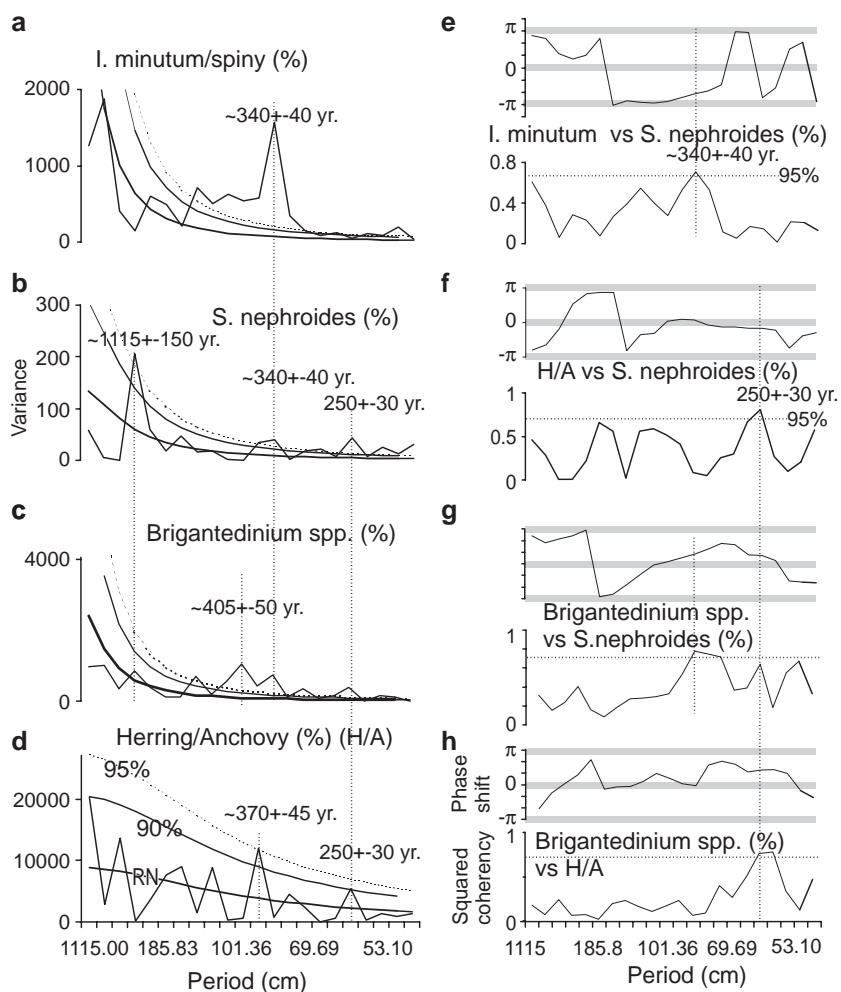


Fig. 6. (a–d) Spectral analysis of fish and dinoflagellate time series from 16 to 1130 cm depth of core TUL99B03, periodograms with red noise levels (RN), 90% and 95% confidence levels for non-randomness. (e–h) Cross-spectral analysis of fish and dinoflagellate time series from 16 to 1130 cm depth of core TUL99B03. Squared coherency (bottoms) and phase spectrum (tops): horizontal grey bars mark in-phase (0) or inverse (+π or -π) cross-correlation. Dotted vertical lines mark periods that are significantly cross-correlated, horizontal dotted lines: 90% or 95% confidence levels.

Similar excursions at lower amplitudes occur at 140–230 cm ($\sim 1200 \pm 130$ to 1700 ± 130 years BP) and at 820–960 cm ($\sim 4000 \pm 130$ to 4800 ± 130 years BP) (Figs. 2,3).

Wavelet analysis and SA show a similar cyclic pattern in fish scale, dinoflagellate cyst and sediment color records in core TUL99B03 that can roughly be grouped into millennial (1100–1400 years), multi-

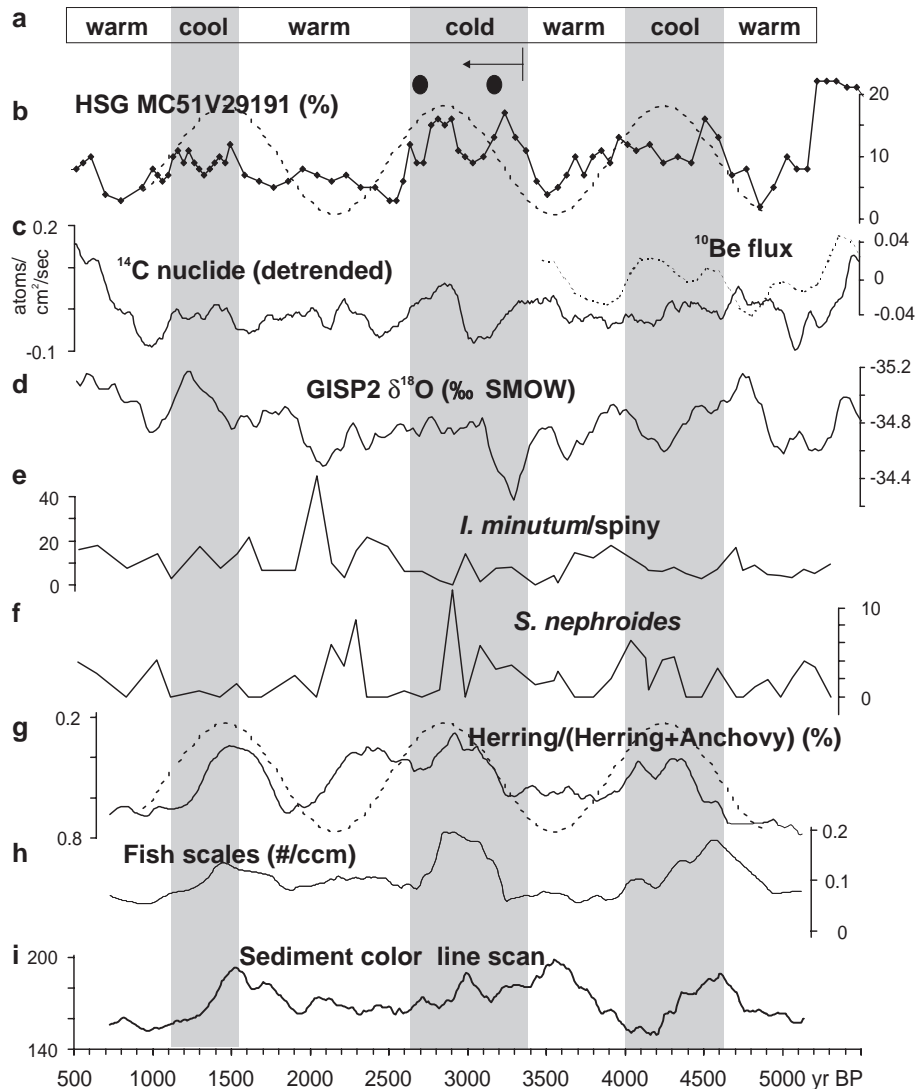


Fig. 7. Compilation of results. (a) Global temperature stages derived from drift-ice debris records (Bond et al., 2001); major Rocky Mountain glacier advances (~ 3300 and 2800 years BP) and vegetation shift at ~ 3460 years BP and (Pellatt and Mathewes, 1997). (b) Percentage of hematite stained grains of section MC51V29191 from the North Atlantic (Bond et al., 2001); dashed line—sinusoidal ~ 1400 -year cycle for comparison. (c) Solid line—detrended cosmogenic ^{14}C nuclide record, 400-year moving average, dotted line— ^{10}Be flux from GISP2 core, 70-year moving average, (Bond et al., 2001). (d) Oxygen isotope record of Greenland ice core GISP2, 200 years moving average (Stuiver and Grootes, 2000). (e–f) Percentages of ecologically sensitive dinoflagellate species of core TUL99B03. (g–i) Fish productivity and sedimentary time series (400-year moving averages) of core TUL99B03; note that 200 years on top and bottom of the time series (g–j) are missing due to the moving average window size; on bottom—depth scale and calibrated time-scale for TUL99B03 (see Fig. 2). Dashed line in panel (g) marks sine curve of a ~ 1400 -year cycle. Grey shaded areas delineate ‘cool’ intervals (after Bond et al., 2001).

centennial (300–410 years) and bicentennial (190–280 years) wavebands (Figs. 5,6). Cycles of ~400- to 800-year duration occur in several records, but they are either limited to a single taxa (e.g., 460-year cycle for RBC, Fig. 5), are of low amplitude, or occur through only a short time interval (Fig. 5).

A millennial-scale cyclicity of 1100–1400 years (~270–350 cm) occurs persistently with amplitudes of >8% in the H/A ratio, >8% in the ‘round brown cysts,’ >0.03 counts/cm³ for fish scales and at weaker amplitudes in other dinoflagellate cyst taxa (Figs. 5, 6). Of particular note is that the ~1110-year cyclicity in the relative abundance of *Selenopemphix nephroides* is statistically significant (>95%) (Fig. 6b). The millennial cycle band tends to be overpowered by the strong variance of high-frequency fluctuation in the sediment color time series (Fig. 5) but emerges after application of a 250-cm moving average (Fig. 7i). In contrast to the high amplitude of this cycle in all biotic time series, there is no cross-correlation at the millennial cycle band between fish scale and dinoflagellate cyst data (Fig. 6e–h).

The multi-centennial ~300- to 410-year (~75–103 cm) cycle band occurs persistently and significantly (>95%) in most biotic and sedimentary time series (Figs. 5, 6a–d). *Selenopemphix nephroides* populations fluctuate inversely in ~340-year cycles with *Islandinium minutum*/spiny and $\sim\pi/3$ phase-shifted with *Brigantedinium* spp. (Fig. 6d). Neither multi-centennial nor shorter cycles have been correlated with other climate proxy records (Fig. 7) because of the stratigraphic ambiguity that is a product of both uncertainty in the radiocarbon dating, and unresolved short-time fluctuations in sedimentation rate at the different sites.

Bicentennial 190- to 280-year (48–71 cm) cycles occur in most time series with significantly high amplitudes (Figs. 5, 6b–d), but are less persistent and have larger amplitude fluctuations than the multi-centennial and millennial cycles (Fig. 5). In particular, this cyclicity is often missing or diminished in the 470- to 660-cm depth (~2650 ± 130 years BP to ~3400 ± 130 years BP; see dashed lines in Fig. 5) interval of the core. Cross-spectral analysis (Fig. 6f,h) reveals that the H/A ratio is significant and positively correlated with high *Selenopemphix nephroides* percentage occurrences in the ~250 ± 30-year waveband and $\sim\pi/2$ (90°) phase shift to *Brigantedinium*

percentages as representatives within PC2 and PC3, respectively (Table 2).

A transition in the cycle pattern occurs at ~3400 years BP. Older sediments are characterized by a highly intense <500-year cyclicity (black bands in the scalograms) while younger sediments display a much less intense cyclicity in both the fish scale and sedimentary data (Fig. 5). At ~2650 years BP another transition in the cycle pattern occurs resulting in less intense sedimentary and biotic fluctuations (Fig. 5).

5. Discussion

5.1. Ecological relevance of dinoflagellate flora

The distribution of the dinoflagellate cysts assemblages was interpreted by visual inspection of the percentage distribution of various taxa through the cores and further by grouping taxa into principal components (PCs). Any environmental interpretation based on dinoflagellate cysts should take into account various limitations of such studies. Generally planktic dinoflagellate populations are selectively fossilized because there are proportionally fewer species of dinoflagellates cysts (Dale, 1983). Environmental conditions controlling encystment of most non-toxic dinoflagellates are also not well understood (Wall et al., 1977; Dale, 1983), and encystment rates of individual species are also known to vary. The problems, uncertainties and limitations of environmental interpretations related to morphological variations observed within various dinoflagellate cyst taxa (for example *Operculodinium* spp., *Islandinium minutum*, and cysts of *Polykrikos* spp.) has been discussed by De Vernal et al. (2001).

Analysis of the dinoflagellate cyst floras indicates that marine influence, including nutrient supply and salinity levels varied considerably in Effingham Inlet, often being much stronger than at present (Kumar and Patterson, 2002). The primary control over the regional distribution of dinoflagellate cysts in the NE Pacific region though is primary productivity and upwelling, as well as the winter temperature gradient (Radi and de Vernal, 2004). Thus climatic and oceanic changes that influence these parameters should be detectable in temporal variation in the Effingham Inlet dinoflagellate cyst assemblages.

The dinoflagellate floras deposited during the regional cold climate interval between ~3400 years BP and 2650 years BP (e.g., Pellatt and Mathewes, 1997) is strongly represented by both a relatively low ‘cold-water’ PC1 and high ‘low-productivity’ PC3. The cold-water indicator *Islandinium minutum*/spiny round brown cysts, an important component of PC1, is at present typical of Arctic-type water masses where water temperatures rarely exceed 7 °C (Head et al., 2001). Although Radi and de Vernal (2004) interpret the presence of *I. minutum* to potentially indicate higher productivity, we find no evidence to support this claim here as PC1 is surprisingly low during this ‘cold’ interval (Fig. 4). Rochon et al. (1999) pointed out that *I. minutum* can tolerate salinities up to 32‰. Considering the high values of the ‘salinity proxy’ PC2 (Fig. 4a), it is possible, that the surface water was too salty for *I. minutum* during the ‘cold’ interval. The interval is also characterized by abundant *Operculodinium* spp., an opportunistic species characteristic of the low nutrient PC3. Thus, the dinoflagellate association suggests relatively low-productivity conditions during this ‘cold’ climate interval.

Temporal fluctuations in the less distinct dinoflagellate assemblages found in sediments younger than ~2650 years BP and older than ~3400 years BP are difficult to interpret in the context of long-term paleoclimate changes. Correlations to other proxies in the core and in the northern hemisphere are not obvious (Fig. 7) or statistically robust (Fig. 6). The ~330- to 340-year (~80–90 cm) cyclicity found in fluctuations of dinoflagellate cyst percentages (Figs. 5,6) cannot be related to known climate. Consequently, we consider that aside from the dinoflagellate cyst assemblages deposited during the cold climate interval between ~3400 years BP and 2650 years BP, the dinoflagellate cyst record in core TUL99B03 records predominantly local changes in salinity and nutrient supply. The relative abundance of *Selenopemphix nephroides* as a salinity proxy shows a good correlation with the regional and global climate proxy record (Fig. 7).

5.2. Statistical link between sedimentation, fish and primary productivity

The dinoflagellate cyst record shows no clear or statistically significant correlation with the fish scale record (Table 2, Fig. 6f,h) in Effingham Inlet, or with

late Holocene northern hemisphere paleoclimate proxy records (Fig. 7). We suggest two possible hypotheses for this lack of correlation:

- (1) Statistical uncertainty: The low dinoflagellate cyst counts obtained in many samples, increases the probability that the percentages obtained for each taxa per sample contains random information rather than the true population mean. Additional uncertainty arises due to the low number of samples examined (48 samples), and bandwidth uncertainty due to the low ratio between the total length of data set (~1130 cm=~4800 years) and sampling interval (~25 cm=~100 years). The fish scale data and sediment color data comprising 112 samples and ~130,000 line-scan data points respectively have a much higher resolution and thus less statistical uncertainty.
- (2) The lumping of taxa in groups that possibly comprise species with different ecological preferences (e.g., *Islandinium minutum*/spiny round brown cysts or RBC) limits the interpretation of the statistical results.
- (3) Decoupling of dinoflagellate productivity from fish productivity and sedimentary pattern formation: It is possible that any ‘Bond’ cycle displayed by the dinoflagellate cyst floras in Effingham Inlet is being suppressed by other, more powerful long-term local environmental changes (e.g., preservational biases, changes in the terrestrial nutrient supply of iron, phosphorus and nitrates, and local cloud cover). Such changes in nutrient availability would impact both photosynthesizing and heterotrophic dinoflagellates. A coeval ‘Bond’ cycle would be expected to be manifested in the percentage occurrence of *I. minutum*. Thus the signal may be subdued in the Inlet due to the known sensitivity of this species to surface water salinities of >32‰, conditions that most likely prevailed during this cold interval.

5.3. Climate cycles and regime shifts recorded in Effingham Inlet Holocene sediments

A bicentennial 200- to 280-year and a multi-centennial 300- to 410-year cyclicity has been noted

in many Holocene climate proxy records throughout the northern hemisphere ('Suess cycle': e.g., [Sonnett and Finney, 1990](#)). It has been suggested that these centennial-scale solar cycles may have been responsible for the 'Maunder' sunspot number minimum (AD 1645–1715) during the Little Ice Age ([Ribes and Nesme-Ribes, 1993](#)). Other Maunder-like minima with the same ~200-year frequency have been documented in mid-Holocene sediments from North America ([Dean et al., 1996](#)) and elsewhere ([Dean, 2000](#)). Similar periodicities have been found in lake sediments in Alaska ([Hu et al., 2003](#)) and in the GISP2 ice core (e.g., [Mayewski et al., 1993](#)).

Unfortunately, a direct correlation between our climate/solar irradiance proxy records at ~200-year wavelengths is not possible at this stage due to limitations caused by time scale accuracy and resolution. Previous time series analysis carried out on fish scale (anchovy, sardines) records for the last 1500 years in the NE Pacific ([Baumgartner et al., 1992](#)) provided ambiguous results with regard to the presence of a bi- and multi-centennial cyclicity as well.

Millennial-scale cycles are pervasive in the fossil and sedimentary data from Effingham Inlet but their wavelengths vary, ranging from 1100 years in the dinoflagellate cyst data, up to ~1400 years in the fish scale data ([Fig. 5](#)). This wavelength difference could be, (1) because the millennial-scale forcing is not strictly periodic but quasi-periodic with a range of ~1100–1400 years, or (2) because dinoflagellate cyst and fish scale abundance have the largest variability at different times. As mentioned above, the fish scale data set is statistically more robust than the dinoflagellate cyst data and more likely to precisely represent the underlying periodicity. Millennial cycles have been noted in several places in the North Pacific realm, for example in biogenic silica fluctuations in a lake in Alaska ([Hu et al., 2003](#)). Millennial-scale relative sea-level fluctuations have also been observed in the NW Pacific that peak during the 'warm' intervals at ~3800 years BP, 2500 years BP, 1000 years BP ([Razjigaeva et al., 2004](#)).

Correlation shows that the millennial cycles of fish scale abundance are in phase with cyclic cooling and warming trends observed in the North Atlantic ([Bond et al., 2001](#)). There is also a more limited correlation with the ^{10}Be record of the GISP2 ice core ([Bond et](#)

[al., 2001](#)) ([Fig. 7](#)). [Wunsch \(2000\)](#) argued that such millennial cycles (e.g., observed narrow-band ~1470 year cyclicity) might be an aliasing artefact arising as a methodological issues related to Fourier analysis of annual (i.e., ~365 days) cycles. However, the millennial cycles found in Effingham Inlet are broad-band and particularly evident in wavelet analysis ([Fig. 5](#)). They are thus unlikely the result of aliasing of an annual signal.

Nevertheless, the observed correlation between the North Atlantic hematite stained grain (HSG) record and the millennial fish scale cycle between ~500 years BP and ~5300 years BP ([Fig. 7](#)) could be coincidental as there are only three observed cycles in the available Effingham Inlet record. Longer marine records along the NE Pacific would be required to determine whether solar or other external forcing, or internal oceanic–atmospheric oscillation are responsible for the observed climate, marine productivity and diversity shifts.

The pattern of sedimentary and biotic fluctuations in Effingham Inlet changed rapidly at 3400 ± 130 years BP, and to a lesser degree at 2650 ± 130 years BP ([Fig. 5](#)). Palynological climate proxy records from sites around British Columbia also indicate an episode of widespread and regionally variable climate change at about ~3400 years BP, which corresponds to the development of neoglacial conditions in the Pacific Northwest ([Pellatt et al., 2001](#)) and in the Coast Mountains of British Columbia ([Ryder and Thomson, 1986](#)). The sedimentary record from nearby Saanich Inlet at the southeast coast of Vancouver Island provides evidence of a change to wetter climate at ~3400 years BP ([Nederbragt and Thurow, 2001](#)). The ~3400-year BP transition in the cycle pattern also corresponds with major regional and northern hemisphere cooling events, as indicated by NE Pacific coast vegetation patterns ([Hebda, 1995](#)) and North Atlantic ice drift records ([Fig. 7b, Bond et al., 2001](#)).

The interval between ~3400 and 2650 years BP represents a cold climate state along the entire NE Pacific coast, with significant Glacial advances at ~3300 and 2900 years BP in the northern Rocky Mountains (e.g., [Pellatt and Mathewes, 1997](#)). There is at present no physical explanation for the relatively rapid changes in biotic and sedimentary cycles at ~3400 years BP and 2650 years BP. It is possible that these observed major and rapid switches in oceano-

graphic cyclicality at that time are analogous to the regime shifts associated with the decadal-scale Pacific Decadal Oscillation (Mantua et al., 1997); but at a much greater magnitude. These abrupt larger scale climate change events may have been triggered as the result of oceanic–atmospheric interactions correlated to the onset of the neoglaciation conditions in the Cascadia region at that time (Pellatt et al., 2001), or as a result of changes in deep-water oceanic circulation (Bond et al., 2001).

5.4. Possible solar forcing of fish stocks in the NE Pacific?

Based on our statistical analysis of the Effingham Inlet data, we have recognized that floral and faunal associations fluctuate at millennial-scale cycles that at least partially correspond to presently observed fluctuations in fish productivity dynamics in the northeast Pacific (e.g., Baumgartner et al., 1992; Chavez et al., 2003).

Two distinctive fish regimes are recognized that persist for considerable periods of time:

- (1) An anchovy-dominated regime that is generally fish-rich (Fig. 7).
- (2) A herring-dominated, fish-poor regime (Fig. 7).

Based on paleoclimate and paleoceanographic evidence (e.g., Bond et al., 2001, Pellatt and Mathewes, 1997) and the distribution of modern fish stocks (Beamish, 1993), it seems that the ‘anchovy regime’ associations occur during relatively cooler periods and at an oceanic salinity of $>35\text{‰}$, because of its association with increased percentages of *Selenopemphix nephroides*. Thus, this cold, high-productivity regime was probably deposited in an oxygen-rich, saline and turbulent water mass that came about as the result of more frequent oxygenation events in the normally anoxic inner basin of Effingham Inlet. In contrast, the herring regime occurred during a warmer period characterized by less saline ($<27\text{–}32\text{‰}$) and nutrient-rich water.

Bond et al. (2001) concluded that the HSG record corresponds to the ^{10}Be flux, and that this ^{10}Be flux records fluctuations in cosmic ray flux and/or solar activity. The excellent correlation between the late

Holocene millennial-scale HSG cycles reported in the North Atlantic region (Bond et al., 2001) and the Effingham Inlet fish scale record (Fig. 7) provides quantitative evidence for a correlation between global cooling and enhanced cold-water habitat fish productivity in the NE Pacific on the millennial-scale, that seems to be at least partially celestially driven. These results provide corroborative evidence that celestial climate forcing is of sufficient intensity to drive climate and marine productivity fluctuations at the millennial-scale (e.g., White et al., 1997; Carlsaw et al., 2002). Similarly, it is likely that the shorter period cycles observed in the NE Pacific marine and terrestrial productivity records (e.g., Suess and Gleissberg cycles), are similarly linked to celestial forcing (Patterson et al., 2004a; Raspopov et al., 2004).

We propose that millennial-scale climate forcing mechanisms influenced late Holocene climate change in the NE Pacific region in the following manner: (1) a decrease in solar activity led to an increase in cosmic ray flux, that in turn resulted in increased lower cloud cover (Carlsaw et al., 2002); (2) the resultant cooling would have stimulated ice-sheet growth in the coastal mountains of British Columbia; (3) the increased albedo generated by these glaciers would have resulted in further cooling and proportionately less oceanic–atmospheric heat transport to the North Pacific; and (4) a simultaneous strengthening of the North Pacific high-pressure system during summer would have resulted in enhanced cold-water, nutrient rich upwelling, which would have stimulated higher productivity amongst cold-water preferring fish species.

Our evidence further indicates that there are quasi-periodic millennial-scale shifts between herring-rich regimes, which dominate during a ‘warm’ climate mode and anchovy-rich regimes, which characterize ‘cold’ intervals. Extrapolation of the observed coherence of these ‘anchovy’ and ‘herring’ regime events from the geologic record (see Fig. 7) indicates that the west coast of Vancouver Island is at present in transition from a ‘cold’ anchovy regime to a ‘warm’ herring regime.

Although this millennial-scale cycle in fish productivity is of potential use to fisheries managers, it has been emphasized that this long-term cycle can easily be influenced in the short term by high-frequency

natural (e.g., Pacific decadal oscillation) or anthropogenic (e.g., overfishing) fluctuations, and is unlikely to be noticeable at short time scales (e.g., through a human generation).

6. Conclusions

- (1) The temporal distribution of eleven dinoflagellate cyst taxa from a late Holocene marine sediment record suggests that from ~500–5300 years BP the inner basin of Effingham Inlet, on the west coast of Vancouver Island has periodically been exposed to more open marine and nutrient richer condition than at present.
- (2) Fish scale and dinoflagellate cyst assemblages as well as sediment color fluctuates at predominantly millennial, multi- and bicentennial scales.
- (3) Millennial-scale fluctuations in fish productivity (herring and anchovy scale records), sediment color changes, and to a certain extent changes in dinoflagellate cyst percentages (e.g., *Selenopemphix nephroides*) display a good coherency with Northern hemisphere climate and solar activity proxy records, suggesting that solar forcing is at least partially responsible for NE Pacific marine productivity fluctuations.
- (4) An ~1400-year scale cyclicity in fish productivity in the region is proposed, which alternates between an anchovy-rich, high fish productivity, highly saline water ‘cold’ regime and a herring-rich, low fish productivity ‘warm water’ regime. Projection of the observed paleoceanographic record forward in time indicates that the NE Pacific is now in the midst of a transition from an ‘anchovy’- to a ‘herring’-dominated regime.

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Appendix A. Taxonomic

Fish taxa

Pacific herring

Clupea harengus pallasi Valenciennes, 1847 (in Cuvier and Valenciennes, 1847)

Northern Anchovy

Engraulis mordax mordax Girard, 1854

Dinoflagellate cyst morphotype taxa

Islandinium minutum (Harland and Reid in Harland et al., 1980)
Head et al., 2001

Quinquecuspis concreta (Reid, 1977)

Selenopemphix nephroides Benedek, 1972 emend. Bujak in Bujak et al., 1980

Votadinium calvum Reid, 1977

Votadinium spinosum Reid, 1977

Undifferentiated *Brigantedinium* Wall, 1965

Undifferentiated *Lejeunecysta* (Reid, 1977)

Undifferentiated *Operculodinium* (Deflandre and Cookson, 1955)

Undifferentiated *Polykrikos* Bütschli, 1873

Undifferentiated *Selenopemphix* Benedek, 1972

Round brown cysts (RBC) Wall et al., 1977

References

- Baumgartner, T.R., Soutar, A., Ferreira-Bartrina, V., 1992. Reconstruction of the history of Pacific Sardine and northern anchovy populations over the past two millennia from sediments of the Santa Barbara Basin. California Cooperative Oceanic Fisheries Investigations Reports 33, 24–40.
- Beamish, R.J., 1993. Climate and exceptional fish production off the west coast of North America. Canadian Journal of Fisheries and Aquatic Sciences 50, 2270–2291.
- Benedek, P.N., 1972. Phytoplanktonen aus dem Mittel- und Oberoligizän von Tönisberg (Niederrheingebiet). Palaeontographica B 137, 1–71.
- Bond, G.C., Kromer, B., Beer, J., Muscheler, R., Evans, M., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., Bonani,

- G., 2001. Persistent solar influence on north Atlantic climate during the Holocene. *Science* 294, 2130–2136.
- Brodeur, R.D., Ware, D.M., 1992. Long-term variability in zooplankton biomass in the subarctic Pacific Ocean. *Fisheries Oceanography* 1, 32–38.
- Bujak, J.P., Downie, C., Eaton, G.L., Williams, G.L., 1980. Dinoflagellate cysts and acritarchs from the Eocene of southern England. The Paleontological Association, Special Paper, *Palaeontology* 24, 1–100.
- Bütschli, O., 1873. Einiges über Infusorien. *Archiv für Mikroskopische Anatomie* 9, 657–678.
- Carslaw, K.S., Harrison, R.G., Kirkby, J., 2002. Cosmic rays, clouds and climate. *Science* 298, 1732–1737.
- Chang, A.S., Patterson, R.T., McNeely, R., 2003. Seasonal sediment and diatom record from late Holocene laminated sediments, Effingham Inlet, British Columbia, Canada. *Palaios* 18, 477–494.
- Chavez, F.P., Ryan, J., Lluch-Cota, S.E., Niquen, C.M., 2003. From anchovies to sardines and back: multidecadal change in the Pacific Ocean. *Science* 299, 217–221.
- Christoforou, P., Hameed, S., 1997. Solar cycle and the Pacific ‘centers of action’. *Geophysical Research Letters* 24, 293–296.
- Cuvier, G., Valenciennes, A., 1847. *Histoire naturelle des poissons*. Tome vingtième. Livre vingt et unième. De la famille des Clupéoides. *Histoire Naturelle Des Poissons* (472 pp.)
- Dale, B., 1983. Dinoflagellate resting cysts: “benthic plankton”. In: Fryxel, G.A. (Ed.), *Survival Strategies of the Algae*. Cambridge University Press, Cambridge, pp. 69–136.
- Dallimore, A., 2001. Late Holocene geologic, oceanographic and climate history of an anoxic fjord: Effingham Inlet, West Coast, Vancouver Island. PhD thesis, Carleton University Ottawa, Ontario.
- Davis, J.R., 1986. *Statistics and Data Analysis in Geology*, 2nd Edition Revised. Wiley, New York.
- Dean, W.E., 2000. The sun and climate. USGS Fact Sheet FS-095-00, 6 pp.
- Dean, W.E., Ahlbrandt, T.S., Bradbury, J.P., Anderson, R.Y., 1996. Regional aridity in North America during the middle Holocene. *The Holocene* 6, 145–155.
- Deflandre, G., Cookson, I.C., 1955. Fossil microplankton from Australian late Mesozoic and tertiary sediments. *Australian Journal of Marine and Fresh Water Research* 6, 242–313.
- De Vernal, A., Henry, M., Matthiesen, J., Mudie, P.J., Rochon, A., Boessenkool, K.P., Eynaud, F., Grosfeld, K., Guiot, J., Hamel, D., Harland, R., Head, M.J., Kunz-Pirrung, M., Levac, E., Loucheur, V., Peyron, O., Pospelova, V., Radi, T., Turon, J.-L., Veronica, E., 2001. Dinoflagellate cyst assemblages as tracers of sea-surface conditions in the northern North Atlantic, Arctic and sub Arctic seas: the new ‘*n=677*’ data base and its application for quantitative paleoceanographic reconstruction. *Journal of Quaternary Sciences* 16, 681–698.
- Girard, C.F., 1854. Descriptions of new fishes, collected by Dr. A.L. Heermann, naturalist attached to the survey of the Pacific railroad route, under Lieut. R.S. Williamson, U. S. A. *Proceedings of the Academy of Natural Sciences of Philadelphia* 7, 129–140.
- Grossman, A., Morlet, J., 1984. Decomposition of Hardy functions into square integrable wavelets of constant shape. *Society for Industrial and Applied Mathematics Journal on Mathematical Analysis* 15, 732–736.
- Hameed, S., Lee, J.N., 2003. Displacements of the Aleutian low and the Hawaiian high pressure systems during the solar cycle. *Eos Transactions American Geophysical Union* 84 (Fall Meeting Supplemental, Abstract SH11E-03).
- Hare, S.R., Mantua, N.J., Francis, R.C., 1999. Inverse production regimes: Alaska and West Coast Pacific salmon. *Fisheries* 24, 6–14.
- Harland, R., Reid, P.C., Dobell, P., Norris, G., 1980. Recent and sub-recent dinoflagellate cysts from the Beaufort Sea, Canadian Arctic. *Grana* 19, 211–225.
- Head, M.J., Harland, R., Mattiessen, J., 2001. Cold marine indicators of the late quaternary: the new dinoflagellate cyst genus *Islandinium*. *Journal of Quaternary Science* 16, 621–636.
- Hebda, R.J., 1995. British Columbia vegetation and climate history with focus on 6 KA BP. *Géographie Physique et Quaternaire* 49, 55–79.
- Hollowed, A.B., Wooster, W.S., 1995. Decadal-scale variation in the eastern subarctic Pacific: II. Response of northeast Pacific fish stocks. *Canadian Journal of Fisheries and Aquatic Sciences* 121, 373–385.
- Holmgren-Urba, D., Baumgartner, T.R., 1993. A 250-year history of pelagic fish abundances from the anaerobic sediments of the central Gulf of California. *California Cooperative Oceanic Fisheries Investigations Reports* 34, 60–68.
- Hsieh, W.W., Ware, D.M., Thomson, R.E., 1995. Wind-induced upwelling along the west coast of North America. *Canadian Journal of Fisheries and Aquatic Sciences* 52, 325–334.
- Hu, F.S., Kaufman, D., Yoneji, S., Nelson, D., Shemesh, A., Huang, Y.S., Tian, J., Bond, G., Clegg, B., Brown, T., 2003. Cyclic variation and solar forcing of Holocene climate in the Alaskan subarctic. *Science* 301, 1890–1893.
- Kumar, A., Patterson, R.T., 2002. Dinoflagellate cyst assemblages from Effingham Inlet, Vancouver Island, British Columbia, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology* 180, 187–206.
- Mann, M.E., Lees, J.M., 1996. Robust estimation of background noise and signal detection in climatic time series. *Climatic Change* 33, 409–445.
- Mann, M.E., Park, J., Bradley, R.S., 1995. Global interdecadal and century-scale climate oscillations during the past five centuries. *Nature* 378, 266–270.
- Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., Francis, R.C., 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* 78, 1069–1079.
- Matsuoka, K., Fukuyo, Y., 1986. Cyst and motile morphology of a colonial dinoflagellate *Pheopolykrikos hartmannii* (Zimmermann) comb. Nov. *Journal of Plankton Research* 8, 811–818.
- Mayewski, P.A., Meeker, L.D., Morrison, M.C., Twickler, M.S., Whitlow, S.I., Ferland, K.K., Meese, D.A., Legrand, M.R., Steffensen, J.P., 1993. Greenland ice core “signal” character-

- istics: an expanded view of climate change. *Journal of Geophysical Research* C98, 12839–12847.
- McQuoid, M.R., Hobson, L.A., 2001. A solocene record of diatom and silicoflagellate microfossils in sediments of Saanich Inlet, ODP Leg 169S. *Marine Geology* 174, 111–123.
- Mudie, P.J., de Vernal, A., Head, M.J., 1990. Neogene to recent palynostratigraphy of circum Arctic basins: results of ODP Leg 104, Norwegian Sea, Leg 105, Baffin Bay, and DSDP Site 611, Irminger Sea. In: Bleil, U., Thiede, J. (Eds.), *Geological History of the Polar Oceans: Arctic Versus Antarctic*, NATO ASI Series C, vol. 308. Kluwer Academic Publishers, Dordrecht, NE, pp. 609–646.
- Nederbragt, A.J., Thurow, J., 2001. A 6,000 year varve record of Holocene sediments in Saanich Inlet, British Columbia, from digital sediment colour analysis of ODP Leg 169S cores. *Marine Geology* 174, 95–110.
- Patterson, R.T., Guilbault, J.-P., Thomson, R.E., 2000. Oxygen level control on foraminiferal assemblage distribution in Effingham Inlet, Vancouver Island, British Columbia. *Journal of Foraminiferal Research* 30, 321–335.
- Patterson, R.T., Prokoph, A., Chang, A., Wright, C., Thomson, R.E., Ware, D.M., 2004a. Holocene solar variability and pelagic fish productivity in the NE Pacific. *Palaeoelectronica* 2004-1.
- Patterson, R.T., Prokoph, A., Chang, A., 2004b. Late Holocene sedimentary response to solar and cosmic ray activity influenced climate variability in the NE Pacific. *Sedimentary Geology* 172, 67–84.
- Pellatt, M.G., Mathewes, R.W., 1997. Holocene tree line and climate change on the Queen Charlotte Islands, Canada. *Quaternary Research* 48, 88–99.
- Pellatt, M.G., Hebda, R.J., Mathewes, R.W., 2001. High-resolution Holocene vegetation history and climate from Hole 1034B, ODP leg 169S, Saanich Inlet, Canada. *Marine Geology* 174, 211–222.
- Prokoph, A., Barthelmes, F., 1996. Detection of nonstationarities in geological time series: wavelet transform of chaotic and cyclic sequences. *Computers and Geoscience* 22, 1097–1108.
- Prokoph, A., Fowler, A.D., Patterson, R.T., 2000. Evidence for periodicity and nonlinearity in a high-resolution fossil record of long-term evolution. *Geology* 28, 867–870.
- Radi, T., de Vernal, A., 2004. Dinocyst distribution in surface sediments from the northeastern Pacific margin (40–60°N) in relation to hydrographic conditions, productivity and upwelling. *Review of Palaeobotany and Palynology* 128, 169–193.
- Raspopov, O.M., Dergachev, V.A., Kolstroem, T., 2004. Periodicity of climate conditions and solar variability derived from dendrochronological and other palaeoclimatic data in high latitudes. *Palaeogeography, Palaeoclimatology, Palaeoecology* 209, 127–139.
- Razjigaeva, N.G., Grebennikova, T.A., Ganzey, L.A., Mokhova, L.M., Bazarova, V.B., 2004. The role of global and local factors in determining the middle to late Holocene environmental history of the South Kurile and Komandar islands, northwestern Pacific. *Palaeogeography, Palaeoclimatology, Palaeoecology* 209, 313–333.
- Ribes, J.C., Nesme-Ribes, E., 1993. The solar sunspot cycle in the Maunder minimum AD1645 to AD1715. *Astronomy and Astrophysics* 276, 549–563.
- Reid, P.C., 1977. Peridiniacean and glenodiniacean dinoflagellate cysts from the British Isles. *Nova Hedwigia* 29, 429–463.
- Rioul, O., Vetterli, M., 1991. Wavelets and signal processing. *Institute of Electrical and Electronics Engineers Signal Processing Magazine* 8, 14–38.
- Rochon, A., de Vernal, A., Turon, J.-L., Matthiessen, J., Head, M.J., 1999. Distribution of dinoflagellate cysts in surface sediments from the North Atlantic Ocean and adjacent basins and quantitative reconstruction of sea-surface parameters. *American Association of Stratigraphic Palynologists Contribution Series* 35, 1–152.
- Ryder, J.M., Thomson, B., 1986. Neoglaciation in the southern Coast Mountains of British Columbia: chronology prior to the late neoglaciation maximum. *Canadian Journal of Earth Sciences* 23, 273–287.
- Schweigert, J.F., 1995. Environmental effects of long-term population dynamics and recruitment to Pacific herring (*Clupea pallasii*) populations in southern British Columbia. In: Beamish, R.J. (Ed.), *Climate Change and Northern Fish Populations*, Canadian Special Publication of Fisheries and Aquatic Sciences, vol. 121, pp. 583–599.
- Schwing, F.B., Murphree, T., deWitt, L., Green, P.M., 2002. The evolution of oceanic and atmospheric anomalies in the northeast Pacific during the El Niño and La Niña events of 1995–2001. *Progress in Oceanography* 54, 459–491.
- Sonnett, C.P., Finney, S.A., 1990. The spectrum of radiocarbon. *Philosophical Transactions of the Royal Society of London* 30A, 413–426.
- Stuiver, M., Grootes, P.M., 2000. GISP2 oxygen isotope ratios. *Quaternary Research* 53, 277–284.
- Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, G., van der Plicht, J., Spurk, M., 1998. INTCAL98 Radiocarbon Age Calibration, 24,000–0 cal BP. *Radiocarbon* 40, 1041–1086.
- Thomson, R.E., Gower, J.F.R., 1998. A basin-scale oceanic instability event in the gulf of Alaska. *Journal of Geophysical Research* 103, 3033–3040.
- Torrence, C., Compo, G.P., 1998. A practical guide to wavelet analysis. *Bulletin of the American Meteorological Society* 79, 61–78.
- Tunncliffe, V., O’Connell, J.M., McQuoid, M.R., 2001. A Holocene record of marine fish remains from the northeastern Pacific. *Marine Geology* 174, 197–210.
- Von Storch, H., Zorita, E., Jones, J.M., Dimitriev, Y., González-Rouco, F., Tett, S., 2004. Reconstructing past climate from noisy data. *Science* 306, 679–682.
- Wall, D., 1965. Modern hystrichospheres and dinoflagellate cysts from the Woods Hole region. *Grana Palynologica* 6, 297–314.
- Wall, D., Dale, B., Lohmann, G.P., Smith, W.K., 1977. The environmental and climatic distribution of dinoflagellate cysts in modern marine sediments from regions in the north and south Atlantic Oceans and adjacent seas. *Marine Micropaleontology* 2, 121–200.

- Ware, D.M., Thomson, R.E., 1991. Link between long-term variability in upwelling and fish production in the northeast Pacific Ocean. *Canadian Journal of Fisheries and Aquatic Sciences* 48, 2296–2306.
- Ware, D.M., Thomson, R.E., 2000. Interannual to multidecadal timescale climate variations in the northeast Pacific. *Journal of Climate* 13, 3209–3220.
- White, W.B., Lean, J., Cayan, D.R., Dettinger, M.D., 1997. Response of global upper ocean temperature to changing solar irradiance. *Journal of Geophysical Research* 102 (C2), 3255–3266.
- Wunsch, C., 2000. On sharp spectral lines in the climatercord and the millennial peak. *Paleoceanography* 15, 417–424.