Solar Activity Expressed in a Modern Varve-Thickness Sequence

Journal:	<i>Canadian Journal of Earth Sciences</i>
Manuscript ID	cjes-2018-0111.R2
Manuscript Type:	Article
Date Submitted by the Author:	02-Aug-2018
Complete List of Authors:	Hughes, Gary; California Polytechnic State University, Statistics Department Adams, Jordan; California Polytechnic State University, Physics Cockburn, Jaclyn; University of Guelph, Geography
Keyword:	Varves, Sunspot Cycles, Paleoclimate, Glacial Energy Balance
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)

SCHOLARONE™
Manuscripts

Solar Activity Expressed in a Modern Varve-Thickness Sequence

Gary B. Hughes^{1*}, Jordan Adams² and Jaclyn M.H. Cockburn³

¹Statistics Department, California Polytechnic State University, San Luis Obispo, CA 93407.

²Physics Department, California Polytechnic State University, San Luis Obispo, CA 93407.

³Geography Department, University of Guelph, 50 Stone Rd East, Guelph ON, N1G 2W1.

*Corresponding author: Gary Hughes (gbhughes@calpoly.edu)

Keywords: Varves, Sunspot Cycles, Paleoclimate, Glacial Energy Balance

ABSTRACT

Annually laminated sediments (varves) form in particular depositional settings, e.g., where seasonal climate produces fluctuations in runoff volume; variations in runoff affect the amount and type of sediment delivered to a catchment. Prior studies confirm that variations in selected varve traits correlate with inter-annual climate signals. In some locations, solar activity also appears to be expressed in varve characteristics, either through a direct effect, or indirectly via influence of solar activity on climate. Evidence from proglacial Iceberg Lake, Alaska indicates that solar activity may have directly contributed to varve deposition. A varve thickness sequence is compared to sunspot observations from 1610-1995 CE. Maunder and Dalton minima are clearly expressed in a varve power spectrogram; varve signal amplification beginning ca. 1950s CE coincides with increasing activity evident in a sunspot spectrogram, features that are only vaguely discernible in the raw time-series plots. Spectral relationships at sunspot periodicities are consistent with direct solar forcing of varve thickness, independent of any effect solar activity might otherwise have on climate. Simulations based on a meltwater model indicate that direct forcing could result from amplified ultraviolet (UV) emission during solar maxima, combined with lower UV albedo of glacial ice. The plausible forcing mechanism bolsters epistemology for concluding a cause-effect relationship: solar variability likely contributed directly to inter-decadal patterns in Iceberg Lake varve thicknesses. The putative

effect could be enhanced at higher latitudes, where Earth's atmosphere absorbs less of the UV energy emitted by the Sun; periods of lowered ozone concentration near the poles would exacerbate the natural abetting UV phenomena, potentially linking human activity to recent and accelerated polar ice cap melting.

1. INTRODUCTION

1.1. Varves as Paleoclimate Indicators

The term 'varve' is used to describe a particular pattern of alternating layers exhibited in some sediments and sedimentary rocks. Varve layers are distinguished by contrasting color and texture that result from annual cycles of deposition. Seasonal temperature and/or rainfall cycles can drive large variations in water volume supplied to a lake or other catchment; variations in water supply affect the quantity and texture of waterborne sediment delivered to the catchment. Seasonal plankton growth can supply varying amounts of organic material, and biogenic silica and carbonate, which mix with the clastic component. Seasonal temperatures that result in intervals of ice-covered and open water can further affect sediment delivery and preservation, e.g., via effects on water column turbulence.

Diverse environmental factors contribute to varve formation, so varved sediments can occur in numerous settings, including marine and lacustrine locales. Varves often form in 'proglacial' lakes, i.e., lakes that have significant influx from glacial meltwater (Zolitschka et al., 2015; Ojala et al., 2012; Lamoureux et al., 2002). Melting of glacial ice is particularly affected by seasonal climate, resulting in large, cyclic variations in meltwater runoff volume. It is also common for proglacial lakes to undergo annual freeze-thaw cycles, augmenting conditions for varve formation. Since annual climate cycles affect glaciolacustrine varve formation, inter-annual climate variability is often expressed in varve characteristics across a sequence of layers

(Lotter and Birks, 1997). Significant correlation has been reported between glaciolacustrine varve characteristics and seasonal temperatures (Thomas and Briner, 2009; Besonen et al., 2008), and precipitation (Lamoureux and Gilbert, 2004, Amann et al., 2015).

1.2. Varve Thickness and Solar Activity

Varves from some depositional settings also express features that correlate with solar activity. Proglacial varve composition was found to correlate with long-period solar variability (Nussbaumer et al., 2011); solar activity influence on alpine climate was readily apparent on time scales from centuries to millennia, but not as easily detected on shorter timescales. Nussbaumer et al. (2011) attribute the solar effect on alpine climate to variations in total solar irradiance (TSI), as reconstructed from ice core ^{10}Be records; the presumed physical mechanism is via atmospheric warming due to variation in broadband insolation, and convectional heating of glacial ice, leading to modulation of meltwater volume. Biogenic components in varved sediments from a non-glacial catchment correspond closely with tree-ring radiocarbon records (Haltia-Hovi et al., 2007), though no physical link between solar activity and sedimentation is proffered. In addition, a non-varved sediment record from Grand Mere Lakes, Michigan, downwind of sand dunes along the coastline of Lake Michigan, showed sunspot cycling with respect to wind-transported sand that may serve as proxies to variations in the pathways of extratropical cyclone activity (Hanes et al., 2014). Both climate and solar ‘signatures’ have been implicated in ancient varve sequences (Hughes et al., 2003; Bracewell, 1988; Sonnet and Trebisky, 1986; Williams and Sonett, 1985).

Observed and hypothesized correlation between varve features and solar activity invites speculation of a direct cause-effect link, i.e., that variations in varve characteristics may be influenced directly by changes in solar activity throughout a solar cycle, and that the varve

response is not an indirect result of any effect that solar variability might otherwise have on climate. A direct causal link between solar activity and varve thickness is explored by comparing the historical sunspot record with a varve thickness sequence from proglacial Iceberg Lake, AK.

1.3. Sunspot and Varve Data

Yearly-average sunspot group number is used as an expression of solar activity. Sunspot group number beginning in 1610 CE (Hoyt and Schatten, 1998) is available at the National Oceanic and Atmospheric Administration (NOAA) National Geophysical Data Center (NGDC):

<http://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-indices/sunspot-numbers/group/>

The daily group sunspot number is defined in Eq. (1) (Svalgaard and Schatten, 2016; Hathaway et al., 2002; Hoyt and Schatten, 1998):

$$R_G = \frac{1}{N} \sum_{i=1}^N k_i 12.08 g_i \quad (1)$$

where N is the number of observers, k_i is the correction factor for observer i , and g_i is the number of sunspot groups reported by observer i . Daily values are averaged over calendar years to produce a yearly-average group sunspot number, displayed in Fig. 1.

Iceberg Lake, AK (60° 46' N, 142° 57' W) was a proglacial lake in southeastern Alaska (Diedrich and Loso, 2012; Loso, 2009). For at least 1500 years, the lake was bounded by an ice dam; in 1999, the lake suddenly emptied completely, likely due to drainage as the ice dam receded. Several cores were recovered from the lakebed, and varve thicknesses were measured in the cores. An Iceberg Lake varve thickness sequence (Loso, 2009) is displayed in Fig. 2, available from the NOAA National Centers for Environmental Information (NCEI, formerly the National Climatic Data Center (NCDC)) Paleoclimatology Archives:

<http://www.ncdc.noaa.gov/paleo/study/6197>

Cyclic co-variation of the two signals is visually evident in some regions of a low-pass filtered time-series plot (Fig. 3); both records display a predominant cyclic mode near the Schwabe periodicity (≈ 11 years), particularly in the latter stages of the record. Varve signal amplitude surges considerably during solar cycle 19 (peak in March, 1958), a period of intensifying solar activity.

1.4. Assessment of a Direct Forcing Hypothesis

The central hypothesis of this study is that variations in solar activity near the Schwabe periodicity directly influenced changes in varve thickness at Iceberg Lake, AK. Furthermore, direct forcing by solar activity is hypothesized to be independent of any effects that solar activity might otherwise have on climate, which could then indirectly influence varve thickness. No claim is made that varve thickness at Iceberg Lake is primarily controlled by solar activity; interannual climate variability is expected to account for a large proportion of variation in varve characteristics across a sequence of layers. However, concluding that solar activity accounts directly for even a small proportion of a glaciolacustrine varve thickness signal is arguably a significant result, due in part to any implications that such direct forcing might hold for glacial energy balance.

Evidence and general arguments are presented to establish a sound epistemology for a cause-effect relationship between solar activity at the Schwabe periodicity and variations in varve thickness at Iceberg Lake. **Section 2** presents a suite of statistical tests for correlation and causation applied to the varve and sunspot records. **Section 3** discusses etiological issues relating to a direct link: comparisons between the two observational records are made by formulating and applying generally discriminating criteria for a causal relationship. **Section 4**

identifies a plausible direct forcing mechanism, and presents a forcing analysis in the specific context of Iceberg Lake. **Section 5** provides a summary of evidence and reasoning that support a solar activity influence on varve thickness at Iceberg Lake, and discusses implications of direct solar forcing for ancient proglacial varves and paleo-solar activity. **Supplementary Material** provides a list of Matlab and R source code files for all analyses (Table S-3), with additional graphs and evidence supporting the statistical, etiological and physical argument for a solar activity influence on varve thickness within the Schwabe frequency band at Iceberg Lake, AK.

2. DESCRIPTIVE STATISTICAL ASSESSMENTS

2.1. Statistical Measures of Bivariate Correlation and Causation

2.1.1. Pearson Correlation

Pearson correlation (r_P , to distinguish from r_{xy} , the sample cross-correlation) between the two data sets is $r_P = 0.335$. A Fisher's Z' test for population Pearson correlation with $H_0: \rho_P = 0$ returns $p < 0.01$ (Fisher, 1936; methods discussed in Section S-3-b). According to the hypothesis test, it is unlikely that the observed correlation would occur between two random and independent signals. However, two major issues encumber the use of Pearson correlation and Fisher's Z' test in this context.

Both methods require that the samples were taken randomly and independently from respective stationary, normally-distributed populations. Normal probability plots provide clear indications of sample non-normality (Fig. S-1). Anderson-Darling tests (Stephens, 1974; NIST Handbook 1.3.5.14) for both samples reject ($p < 0.05$) a null hypothesis of population normality. A Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test (Kwiatkowski et al., 1992) rejects ($p < 0.01$) a null hypothesis of level stationarity for both data series. The varve thickness data is also trend non-stationary (KPSS $p < 0.01$), and the sunspot group number data is at best marginally trend

stationary (KPSS $p = 0.057$). It is reasonable to conclude that neither signal came from a normally-distributed population, and either one or both of the processes are not stationary.

Confidence intervals for Pearson correlation and Fisher's Z' test may be inaccurate, since assumptions about population normality and process stationarity are not met. Specifically, the sampling distribution of Pearson Correlation may not be normal. A confidence interval based on a normal distribution may be too small, leading to a false positive error rate that is larger than the specified value of α . With a confidence interval that is incorrectly narrow, there is more chance of concluding a significant correlation when in fact no population correlation exists. Confidence may be too high that the observed result $r_p = 0.335$ indicates a significant correlation between the varve and sunspot processes. A permutation test for Pearson correlation makes fewer assumptions about population distributions (see, e.g., Hesterberg et al., 2005; methods discussed in Section S-3-b). For $r_p = 0.335$, correlation between 500000 permutations of the solar and varve signals returns a permutation p -value of essentially 0, indicating is highly unlikely that the observed Pearson correlation could have resulted from a random arrangement of the solar activity and varve signals.

Pearson correlation is not strictly germane for describing correlation between two time-series signals: a forcing scenario does not necessarily include two random signals. The hypothesized forcing signal (solar activity) provides a fixed pattern, as observed, and is compared with random response signals. A discerning question is whether the observed measure of correlation is uncommon among many such comparisons. Confidence intervals based on such statistical 'bootstrapping' simulations provide benchmarks to assess the likelihood that observed measures of correlation could have resulted by chance (see, e.g., Hesterberg et al., 2005).

Methods described in Section 2.2.2 are utilized to create random response signals with statistical and spectral characteristics similar to the varve sequence.

The 95% one-sided upper confidence value ($CV_{1,U}$) for r_P produced from 500000 bootstrapping simulations is 0.2006; a histogram of bootstrap correlation values is illustrated in Fig. S-2. The 95% $CV_{1,U}$ for Fisher's Z' test is 0.0569. The observed Pearson correlation between the sunspot and varve data ($r_P = 0.335$), is greater than both the Fisher's Z' and bootstrap 95% $CV_{1,U}$. The bootstrap comparison implies that the observed linear correlation is not likely to be the result of a random response to the solar activity signal.

2.1.2. Sample Cross-Correlation

The observed sample cross-correlation at varve-lag 1 is $r_{xy}(1) = 0.3345$. A $CV_{1,U}(Z_{.05})$ for sample cross-correlation (for independent populations) with a sample size of $n = 386$ is constant across all lags at 0.0837. The $CV_{1,U}$ is used since only positive (and not negative) cross-correlation at short, positive varve lags is relevant to the hypothesized forcing scenario. The varve and sunspot samples do not meet the conditions of the cross-correlation confidence bound (stationarity), The bootstrap 95% $CV_{1,U} = 0.2001$. The sample cross-correlation at short, positive varve lags is greater than both the $Z_{.05}$ and bootstrap 95% $CV_{1,U}$ upper bounds (see Fig. S-3), indicating that the observed sample cross-correlation at lags of interest for the solar forcing scenario is not likely to be the result of a random varve response when compared to the solar activity signal.

2.1.3. Granger Causality

Granger causality (Barnett and Seth, 2014; Seth et al., 2011) is assessed, using model order 9. Model consistency is 84%, adjusted $r^2 = 0.82$, and all residuals are 1-lag uncorrelated by Durbin-Watson test (Durbin and Watson, 1951) at $\alpha = 0.05$. Sunspot Granger causation of

varve thickness returns $p < 0.01$ against a null hypothesis of no causation. The false positive error rate may be misrepresented by the test, since both samples indicate non-stationary processes. Specifically, confidence may be too high that the observed result indicates a significant cause-effect relationship between the varve and sunspot processes. The chance that the test incorrectly indicates a significant relationship is very likely to be higher than 0.01.

2.2. Assessment of Correlation in the Frequency Domain

2.2.1. Discrete Fourier Transform (DFT) Periodogram Peak Amplitude Spectra

Visual correlation in the time-series plot is corroborated by corresponding features in Discrete Fourier Transform (DFT) periodogram peak amplitude spectra (Fig. 4) (methods described in Section S-3-b). DFT spectra of both signals display significant power ($\alpha = 0.05$) near 0.093 cycles per year (10.75 year period) in the Schwabe range. Both signals display a pink noise component, i.e. the amplitude spectrum is characterized by increasing amplitude at lower frequencies, approximated by $1/f^\alpha$, with $0 \leq \alpha \leq 2$. Significance of spectral peaks near the Schwabe periodicity above the pink-noise background is assessed using a spectral model for pink noise.

Confidence limits for spectral peaks are based on a χ^2 -distribution for the ratio of periodogram power to a pink-noise regression model (Vaughan, 2005). Pink-noise elements of the measured signals are characterized with a spectral estimator model defined as a function of frequency Eq. (2):

$$\hat{Y}(f_k) = \sqrt{\gamma^2 + (\alpha f_k^\beta)^2} \quad (2)$$

A non-linear least squares algorithm is used to determine the best-fit spectral estimator parameters. The forcing hypothesis is restricted to the Schwabe periodicity, near 10.75 years, but with a fairly broad spectral peak. Model calculation excludes the spectral region within the

hypothesized forcing band, so that the model and the response are independent at the frequencies of interest. Frequencies within the forcing band are determined from DFT basis indices where the sunspot peak amplitude spectrum are enhanced, selected by visual inspection of the unpadded DFT spectrum in the region $f_{32} = 0.0829$ cpy to $f_{48} = 0.1244$ cpy, inclusive, (8.04-12.06 year periods) (shaded bands in Fig. 4). Regions of the spectrum excluded from the model determination also include f_0 and $f_{n/2}$ (n even), since power in those basis components is not distributed in the same way as components that have a mirror at negative indices.

The pink noise models form a basis to establish confidence limits for spectral peak significance. The ratio of power in the DFT spectrum to baseline signal power level established by the model follows a χ^2 -distribution with 2 degrees of freedom (d.f.) (Antoni, 2007), as shown in Eq. (3):

$$\frac{2 \bar{A}_k}{\hat{Y}(f_k)} \sim \chi^2_2 \quad (3)$$

The theoretical distribution is used to establish confidence limits. A $CV_{1,U}$ is used, since power levels below the model do not constitute enhanced spectral power which would be expected from the hypothesized forcing relationship. The 95% χ^2 - $CV_{1,U}$ is given in Eq. 4:

$$1 - \alpha = \int_{-\infty}^{\chi^2_{\alpha,2}} \frac{1}{2} e^{-\frac{t}{2}} dt \rightarrow \chi^2_{0.05,2} = 5.99146 \quad (4)$$

Substituting the critical value from Eq. (4) into the power relation of Eq. (3) and taking square root produces the $CV_{1,U}$ for peak amplitude at each DFT basis frequency (Eq. (5)):

$$(CV_{1,U})_{.05}(f_k) = \hat{Y}(f_k) \sqrt{\frac{\chi^2_{0.05,2}}{2}} \quad (5)$$

Confidence intervals based on the best-fit spectral model and Eq. (5) are plotted with the DFT peak amplitude spectrum and best-fit spectral estimator in Fig. 4. The χ^2 -confidence bound of

Eq. (5) for periodogram spectral peaks is verified by simulation with random signals. Outside of the spectral region used to estimate the best-fit model, during 500000 simulated runs with random signals, 7.012% of simulated peak amplitude values in the model non-exclusion frequency range were above the estimated 95% $\chi^2-CV_{1,U}$. At least some of the observed power in the varve signal near the frequency band relevant to hypothesized solar forcing is above the 95% $\chi^2-CV_{1,U}$, and thus not likely to result solely from the pink-noise component of the varve process.

2.2.2. Creation of Random Pink Noise Signals for Bootstrapping Analyses

Random response signals used for bootstrapping must possess statistical and spectral characteristics similar to the observed ‘response’. Pink noise properties may be an intrinsic feature of both sunspot and varve processes. In such a case, long-period variability in the observed signals would be independent. Random response signals based on band-limited white noise would not emulate the long-period character of the varve signal; thus, using white-noise signals for bootstrapping responses may underestimate the mean value of correlation sampling distributions. If the bootstrapping mean is an underestimate, then the false positive error rate for hypothesis tests based on the bootstrap confidence intervals will be misrepresented by the bootstrap test. Specifically, confidence would be too high that a bootstrap test indicating significant correlation between the varve and sunspot processes under a scenario that no population correlation exists. To have a better chance of attaining a desired false positive error rate, a pink noise component must be included in the random signals.

The spectral model of Eq. (2) is used to create random pink noise signals with prescribed statistical and spectral characteristics (Hughes, 2017). A band-limited white noise sequence is created. DFT coefficients of the zero-mean white noise sequence are calculated, then modified

250 to vary around the desired spectral profile, and such that the total power in the random sequence
 251 equals power in the varve sequence (Eq. (6)):

$$\bar{A}'_k = \bar{A}_k \left(\sqrt{\gamma^2 + (\alpha f_k^\beta)^2} \right) \frac{\sum_{i=1}^n (\bar{V}_k)}{\sum_{i=1}^n (\bar{A}_k)} \quad k = 1, 2, \dots, n \quad (6)$$

252 where $\bar{A}_k$ is the modulus of the k^{th} band-limited white noise DFT coefficient corresponding to
 253 DFT frequency f_k ; α , β and γ are the pink-noise model coefficients; $\bar{V}_k$ is the modulus of the k^{th}
 254 varve DFT coefficient; and n is the sample size. The new modulus values $\bar{A}'_k$ approximately
 255 follow the modeled pink noise spectral profile, and contain the same total spectral power as the
 256 varve sequence. The new modulus values are used to create DFT coefficients for the pink
 257 random signal (Eq. (7)):

$$\begin{aligned} a'_k &= \bar{A}'_k \cos(\varphi_k) \\ b'_k &= \bar{A}'_k \sin(\varphi_k) \quad k = 0, 2, \dots, n-1 \\ C'_k &= a'_k + i b'_k \end{aligned} \quad (7)$$

258 where φ_k is the argument of the k^{th} band-limited white noise DFT coefficient. The modified
 259 values C'_k become DFT coefficients that follow the desired spectral profile, scaled to the same
 260 total spectral power as the reference sequence. Inverse DFT using the C'_k produces a time-series
 261 sample with the desired pink noise spectral profile. Typical simulated pink noise signals are
 262 shown in Fig. S-5.

263 2.2.3. Maximum Entropy Method (MEM) Spectra and Short-Time Spectrograms

264 Power near the Schwabe periodicity is evident in the Maximum Entropy Method (MEM)
 265 (Press et al., 2007) spectra of both variables (Fig. 5). Peaks at coincident frequencies are

consistent with a forcing relationship between the two variables. Additional MEM spectral peaks in the varve thickness spectrum do not correspond with features in the sunspot spectrum, and may be related to climate forcing.

Both varve and sunspot records express changes in spectral content over time, both displaying increasing amplitude in the latter stages of the interval compared with the beginning of the record. Short-time MEM (STMEM) is employed to explore changes in spectral content. Narrow Gaussian windows centered on each point across the time interval are used to produce STMEM spectrograms (Fig. 6). The spectrograms present visually intriguing co-evolution patterns of prominent spectral features. Maunder (1645-1715 CE) and Dalton (1796-1820 CE) minima are discernible as pan-spectral lulls in both spectrograms. Spectral content in the varve signal strengthens as the solar cycle intensifies.

2.2.4. DFT Cross-Spectrum Phase and Squared Coherence

The DFT cross-spectrum is used to estimate phase relationship and magnitude-squared coherence between the two signals (Fig. 7) (methods described in Section S-3-c). Positive phase difference at the Schwabe periodicity indicates a sunspot-lead relationship, consistent with a solar forcing hypothesis. Magnitude-squared coherence is a measure of the scaled covariance between signal components at individual DFT basis frequencies. A bootstrap 95% $CV_{1,U}$ for cross-spectrum coherence over the 'forcing' frequency band is also shown in Fig. 7b, produced from 500000 simulations. Observed magnitude-squared coherence between the varve and sunspot records within the hypothesized forcing region is not likely due to a random response to the solar activity signal. The bootstrap confidence interval applies only within the forcing frequency band, since it is the only region where the simulated signals are independent of the

white-noise model. Significant coherence may also be present outside the forcing frequency band, which could be induced by a sun-climate-varve connection.

Short-time DFT (STDFT) spectrograms display changes in phase and coherence across the observation interval (Fig. 8) using a window width of $s = 200$ years. The relatively wide window is chosen to provide smoothing of the noisy DFT spectra. Spectrograms with narrower window widths display similar patterns, with varying degrees of clarity in the evolution of features across time. Frequency bands relevant to the solar forcing hypothesis stretch horizontally across the spectrograms, spanning a narrow vertical region around 0.1 cpy. The smoothed phase-difference spectrogram indicates that the phase relationship between the two signals is essentially constant across the time interval within the frequency band of interest. The coherence spectrogram indicates consistently high cross-spectrum coherence across the time interval within the frequency band of interest. Furthermore, cross-spectral coherence increases in the latter stages of the interval as solar activity strengthens. All features are consistent with a solar forcing scenario.

2.2.5. Cross-Cyclic Power Spectrum and Cyclic Spectral Coherence Function

The varve and sunspot records express a fundamental mode that appears to be amplitude-modulated by an underlying lower-frequency signal. The ostensibly cyclostationary character is investigated via a cross-cyclic power spectrum, which describes the cross-spectral density for pairs of frequency-shifted versions of the two data series. Sample cyclic cross-spectral coherence (CCSC) is calculated (Hodder et al., 2007) (Fig. 9). Confidence bounds are displayed over the complete cyclic frequency domain; the observed CCSC exceeds the 99% upper bound at cyclic frequencies that may be associated with inter-decadal amplitude variations in the solar

signal. The observed sample CCSC is not likely to be produced by a random response to the solar activity signal.

3. ETIOLOGY

3.1. General Observations Regarding the Manner of Forcing

To this point, descriptive comparisons between the varve and sunspot records have been reviewed. Conventional confidence bounds are presented (where available) for the descriptive measures. The varve and sunspot signals do not meet the assumptions for most conventional tests, so permutation and bootstrap confidence bounds are established for descriptive measures. In every case, the observed value of the descriptive measure is outside of both the conventional and bootstrap confidence bounds. The analytical results all support the same conclusion: that patterns observed in the varve thickness sequence at Iceberg Lake are not likely to be the result of a random response to the solar 'forcing' signal.

Correlation cannot form a basis for concluding a causal link. An etiology can be advanced by formulating and applying generally discriminating criteria for causal relationships among correlated time-series records. The Henle-Koch-Evans (HKE) postulates (Evans, 1976) were developed (and reformulated over time) to establish causation of disease by microorganisms. Analogs of HKE postulates are adapted for the specific context of two observational records, where one process is hypothesized to have a direct effect on the other; the general criteria are applied to the varve and sunspot series to assess etiological consistency.

Effect cannot precede a putative cause: time-series plots (Fig. 3) and cross-spectrum phase difference plots (Figs. 7, 8) both indicate a sunspot-lead, varve-thickness-lag relationship at the Schwabe periodicity. Changes in solar activity precede the varve signal by ~1.89 years on average, and the relationship is consistent through many solar cycles. Effect must not be

observed in the absence of the putative cause: the varve signal amplitude is suppressed during both Maunder and Dalton minima, and amplified during periods of more vigorous solar activity.

Extraneous variables must not affect the putative cause and response at the forcing frequency: Earth's climate does not affect solar activity, rejecting any reasonable skepticism that both signals are forced by a common natural climate process. Solar cycles are likely an intrinsic feature of the Sun, reducing the likelihood that both signals could be forced by a common source within or outside the solar system, e.g. cosmic ray flux. Potential effects of climate on varve-thickness at Iceberg Lake near the Schwabe periodicity are discounted due to low temporal and spectral correlation with measured regional climate variables (regional temperature and precipitation are discussed in Section 3.4).

Effect should be observed wherever the putative cause is present. Note that Koch (1891) developed a similar tenet before knowledge of asymptomatic carriers was attained; the tenet is highly modified or abolished in subsequent etiological paradigms (Evans, 1976). Analogous logic would permit a lack of correlation between glaciolacustrine varve-thickness and solar activity at other locations, without indicating a counterexample to the hypothesized forcing mechanism at Iceberg Lake. Nonetheless, observed correlation between varve thickness and solar activity at Iceberg Lake should spur curiosity about whether similar evidence is present in other glaciolacustrine varves. Varve-thickness sequences at other locations are already known to correlate with aspects of local climate (Amman et al., 2015; Thomas and Briner, 2009; Besonen et al., 2008; Lamoureux and Gilbert, 2004; Blass et al., 2003; Lotter and Birks, 1997), and express varying degrees of association with solar activity.

Correlation between solar activity and proglacial varve sequences at other sites examined for this study (Table S-1) is either not discernible, or weakly expressed. A varve-thickness

record from Big Round Lake, a proglacial lake on northeast Baffin Island, Arctic Canada (69°52'N 68°51'W) (Thomas and Briner, 2009), is available at the NOAA NCEI Paleoclimatology Archives:

<https://www.ncdc.noaa.gov/paleo-search/study/6203>

Plots and analyses used to explore a forcing relationship at Iceberg Lake are presented for Big Round Lake. A low-pass filtered time-series plot of the Big Round Lake varve-thickness sequence and group sunspot number (Fig. S-13) suggests that further scrutiny is warranted. DFT and MEM spectra (Fig. 10) indicate slight enhancement of power within the hypothesized forcing band. Coherence and STMEM spectrogram (Fig. S-14) at Big Round Lake display many of the same features observed at Iceberg Lake.

The Big Round Lake spectra contain additional prominent features that are likely associated with climate variability. Solar activity influence at Big Round Lake and other sites is potentially obscured or annihilated when glacial meltwater flows over non-glacial terrain through intermediate catchments on the path to the lake (Hodder et al., 2007; Blass et al., 2003). Sediments in intermediated catchments may only advance during dynamic weather events, which would then manifest as a climate correlation in the varve-thickness sequence. Varve-thickness sequences could conceivably express both climate and solar signals, such as in depositional environments that receive influx of similar magnitude and proximity from both glacial and non-glacial sources. Weak correlation between solar activity and varve thickness at a given site does not preclude a solar activity influence in the region, as expression of solar activity forcing on glaciolacustrine varve thickness may be rare, as the circumstances required for a clear expression may be geographically and physically constrained. Specifically, lack of a solar activity signal in other glaciolacustrine varves does not constitute a global counterexample to the hypothesized

forcing relationship at Iceberg Lake. Cited comparisons between observed sunspot group number and Iceberg Lake varve thicknesses are consistent with solar forcing at the Schwabe periodicity, and do not present any clear contradiction of the cause-effect hypothesis.

3.2. Band-Limited Forcing

The spectral content of the varve signal that is ostensibly attributable to a pink noise component accounts for much of the total signal power. Consequently, power near the Schwabe periodicity explains only a small proportion of total variance in varve thickness at Iceberg Lake. A measure of the proportion of power near the Schwabe periodicity is calculated from the DFT peak amplitude spectrum, using an expression of the ratio of power in the region of interest to power in the rest of the signal, such as by Eq. (8):

$$\frac{\sum_{i=32}^{48} (\bar{V}_k^2 \Delta f - \hat{Y}_k^2 \Delta f)}{\sum_{i=2}^{31} (\bar{V}_k^2 \Delta f) + \sum_{i=32}^{48} (\hat{Y}_k^2 \Delta f) + \sum_{i=49}^{\frac{n}{2}} (\bar{V}_k^2 \Delta f)} \approx 0.1208 \quad (8)$$

where $\bar{V}_k$ is the modulus of the k^{th} varve DFT coefficient; $\bar{Y}_k$ is the value of the pink noise model evaluated at the k^{th} DFT frequency, and n is the sample size. Presumably, climate variability accounts for some power in the Iceberg Lake varve thickness spectrum. The current study is not attempting to explain the origins for the bulk of power in the varve signal; rather, the central hypothesis is that variations in solar activity near the Schwabe periodicity directly influenced changes in varve thickness at Iceberg Lake. An explanation is sought for the slight but apparent increase in power in the varve thickness DFT spectrum near the Schwabe periodicity.

3.3. Implications of Chronological Uncertainty in the Varve Record

Presumably, the sunspot record has little or no chronological uncertainty, *i.e.*, the time associated with each sunspot observation is accurate to within approximately ± 0.5 years, for every observation. However, the Iceberg Lake varve age model uncertainty is $\pm 4\%$ per century (Loso, 2009). It is appropriate to address what effects any varve counting errors might have on spectrum analysis. Single varves occasionally go uncounted, *e.g.*, suppose an uncounted varve occurred on average once every 25 years, resulting in a cumulative (unidirectional) age error. Missed layers that should be there but were not counted were added into the sequence as a 0-thickness layer in random places, moving subsequent observed values to the right in the sequence. The MEM power spectrum still has a similar shape, but is ‘compressed’ in the frequency domain by a factor of 1.04. Allowing for uncounted varves every 25 years does not significantly alter the association of spectral peaks in the Iceberg Lake varve thickness and sunspot records.

Occasional addition of ‘phantom’ layers could occur, *i.e.*, suppose an interruption occurred during seasonal sediment delivery that resulted in a single annual unit being misinterpreted as two annual units. Such ‘phantom’ layers would have the opposite effect on the spectral profile, *i.e.*, a stretching of the spectrum above the frequency domain, again without significant changes in the profile shape. Any combination of uncounted and ‘phantom’ varves would diminish the scaling effect as compared to consistently one-directional errors. More radical scenarios would have larger effects on the spectral profile, but would be inconsistent with the stated chronological uncertainty. The pattern of phase difference through time at a period of 10.6 years suggests that counting errors are not substantial or unidirectional. The pattern suggests a $\sim +1$ year discrepancy near the end of the varve record in 1995 CE. The discrepancy can be reconciled by a difference between the seasonal phase attributed to the beginning of a

varve and the seasonal phase of the yearly-averaged sunspot signal. As the age of the varve sequence increases, the phase spectrogram suggests that slightly more ‘phantom’ counting errors occur than missing layers. The presence of age uncertainty in the varve record does not undermine the interpretation of a consistent phase relationship between the two signals, with solar activity leading varve thickness throughout the entire record. See Fig. S-6, which displays time series and MEM spectra of the original varve thickness sequence at Iceberg Lake, alongside a hypothetical series that includes counting errors.

3.4. Regional Climate Data

It is possible that varve thickness at Iceberg Lake is primarily reacting to changes in climate. Glaciolacustrine varve characteristics in many locations correlate with seasonal temperatures (Thomas and Briner, 2009; Besonen et al., 2008), and precipitation (Lamoureux and Gilbert, 2004; Amann et al., 2015). If solar activity influences inter-annual variations in climate, and the varves at Iceberg Lake are then reacting to solar-activity-induced climate variability, then the observed correlation between solar activity and varve thickness would not result from direct forcing by solar activity. Such an indirect forcing relationship can be evaluated by examining historical climate variables in the region of Iceberg Lake.

A secondary varve-thickness effect via a climate intermediary would be supported by oscillations in relevant climate variables at the Schwabe periodicity. Measurements of local climate variables are not available for Iceberg Lake, so climate data recorded in the region of Iceberg Lake is used. Daily measurements of temperature and precipitation from southeastern Alaska and western Canada are available at the NOAA Global Historical Climatological Network (GHCN):

<https://www.ncdc.noaa.gov/cdo-web/search?datasetid=GHCND>

GHEN records for stations (Table S-2) were accessed, chosen based on proximity to Iceberg Lake and length of record. Daily time series of temperature and precipitation spanning 78.64 years were extracted from the database. Time series plots of station-average values are displayed in Fig. S-7, and low-pass-filtered time series are displayed with the Iceberg Lake varve record in Fig. S-8. Analyses of time- and frequency-domain correlation between the Iceberg Lake varve thickness and sunspot records are repeated for the regional temperature and precipitation records. In every case, no indication of significant correlation between climate and the varve thickness sequence is evident within the Schwabe frequency band.

Observed Pearson and sample cross-correlation are both below the bootstrap 95% $CV_{1,U}$ (Figs. S-9, S-10). DFT peak amplitude spectra for both climate data series are displayed in Fig. 9, and MEM power spectra are displayed in Fig. S-11. A pink noise element is apparent in the temperature spectrum, but less so for precipitation. No distinct spectral features are observed within the Schwabe periodicity for either variable; only one DFT component rises above the pink-noise confidence limit, at the edge of the Schwabe band in each spectrum, and several DFT components are below the pink noise model. The pattern within the Schwabe band of temperature and precipitation spectra is noticeably different than the Iceberg Lake varve spectrum. Spectra calculated with other methods (wavelets, MTM, cyclospectrum) also do not display distinct features related to the Schwabe periodicity in either climate record. Neither the temperature nor the rainfall series display perceptible increasing amplitude in the latter stages of the record. Presence of an intermediary effect on varve thickness via solar-activity-induced atmospheric warming with convectional transfer to the ice field would seem to require that spectral correlation be observed in all three signals. If temperature is not varying cyclically at the Schwabe periodicity, then temperature is not responding directly to changes in solar activity,

and temperature cannot be directly causing variations in varve thickness at the Schwabe periodicity.

Temperature and precipitation are intuitive choices for climate variables that may affect varve deposition, but other climate variables could conceivably influence sediment delivery. Many proglacial varve sequences contain a sand component. For example, aeolian deposits can accumulate on an ice-covered surface, and fall through to the lakebed when the ice melts (Lamoureaux et al., 2002; Lewis et al., 2002). Reported correlation between aeolian sand content in (non-varved) lake sediments and long-period solar activity (Hanes et al., 2014) suggests that sun-driven wind patterns could contribute to fluctuations in sediment delivery. Assessing a connection between wind and varve thickness at Iceberg Lake is hampered by the availability of historical data: records of wind speed for the stations near Iceberg Lake begin in 1984 CE. Time series and DFT spectrum plots (Fig. S-12) indicate no power enhancement in the Schwabe band. Even though much of the wind speed data extends beyond the time interval of the Iceberg Lake varve thickness record, lack of any Schwabe-like power in the wind speed spectrum creates obstacles for a hypothetical link between the two variables within the Schwabe periodicity.

Lack of a Schwabe signal in the temperature, precipitation and wind speed power spectra does not completely preclude an intermediary climate effect on varve thickness. A Schwabe effect on climate could be present in other climate variables. A climate intermediary may also be possible without main-mode power in any climate variables, e.g., a non-linear interaction between two climate variables could produce an additive or subtractive mode within the Schwabe region that influences varve deposition. The station-averaged climate data may not be representative of the local conditions at Iceberg Lake, particularly for wind speed, which might

display more extreme local variation than temperature or rainfall. Other scenarios may also be conjured, with varying levels of complexity in a hypothetical relationship that could explain the pattern of power in the varve-thickness signal. The likelihood of more complex forcing scenarios should be discounted, particularly if direct forcing is plausible (discussed in Section 4).

4. FORCING ANALYSIS

4.1. A Putative Physical Mechanism

A known or plausible physical mechanism must be capable of producing the measured response with observed changes in magnitude of the hypothesized cause. Peak amplitude variations in varve thickness at Iceberg Lake during solar cycles 21 (peak in December 1979) and 22 (peak in July 1989) were ~7 mm and ~5 mm, respectively. Satellite measurements indicate a peak amplitude variation in (broadband) total solar irradiance (TSI) during solar cycles 21 and 22 was ~1 W m⁻² (Fröhlich and Lean, 2004; Willson, 1997; Willson and Hudson, 1991).

However, the broadband TSI increase is not evenly distributed. Based on satellite observations, appreciable increases in ultraviolet (UV) irradiance (200–400 nm) occur during solar maximum, with corresponding decreases at optical wavelengths (Fröhlich and Lean, 2004; Lean et al., 1997). Spectral albedo of snow-covered ice decreases markedly from visible (0.95 near 600 nm) into UV wavelengths (0.80 near 380 nm, and decreasing toward shorter wavelengths) (Malinka et al., 2016, Grenfell and Perovich, 1984). The abetting tandem of increased UV irradiance and decreased spectral albedo of glacial ice in UV wavelengths infers that differential meltwater volume could be produced throughout a solar cycle, with concomitant changes in sediment influx to a proglacial lake. The putative response would be directly related to solar activity, and independent of climate effects on glacial melting.

4.2. A Meltwater Forcing Model

A model is developed to predict changes in meltwater volume as a result of the abetting UV phenomena. Daylight-hour energy flux over a glacial surface area is calculated from potential clear-sky insolation. A specified effective broadband albedo determines absorbed energy, which supplies latent heat of fusion to the ice, creating meltwater. Summing daily meltwater totals during a specified melt season produces an estimate of total seasonal meltwater volume, per Eq. (9), which is modified slightly from the model developed by Yong et al. (2007) to include solar cycle phase influence on albedo and insolation (terms defined in Table 2):

$$\hat{V}_{MS} = \sum_{d \in MS} \left[V_C(d) + \frac{[1 - \alpha_e(\varphi_\odot)] A_W}{\rho \Delta H_f} \int_{t \in d} \hat{I}(\varphi_\odot, d, t) dt \right] \quad (9)$$

The effective albedo term $\alpha_e(\varphi_\odot)$ is implemented as a free parameter, with estimated values based on observations of spectral albedo in optical wavelengths (Malinka et al., 2016). The references do not provide measurements of ice spectral albedo into UV-A (315–400 nm) and UV-B (280–315 nm) wavelengths.

The insolation term $I(\varphi_\odot, d, t)$ is estimated using a function of solar irradiance at the top of the atmosphere, baseline atmospheric transmission, solar geometry and topographic characteristics, modified from Yong et al. (2007) as given in Eq. (10) (terms described in Table 3):

$$\hat{I}(\varphi_\odot, d, t) = S(\varphi_\odot) \left[\frac{r_0}{r(d)} \right]^2 \left(\bar{\psi}^{\frac{P}{P_0 \cos Z(t)}} \right) \{ \cos \beta \cos Z(t) + \sin \beta \sin Z(t) \cos[\phi(t) - \theta] \} \quad (10)$$

4.3. Meltwater Simulations

Daily meltwater volume produced by convective heat transfer from the atmosphere, $V_C(d)$ in Eq. (9), is unknown for Iceberg Lake. Under an assumption that the convective component is statistically stationary on time scales of a solar cycle, a solar activity component of total meltwater can be isolated, as in Eq. (11):

$$\hat{V}_S(\varphi_{\odot}) = [\hat{V}_{MS} - \bar{V}_C] = \sum_{d \in MS} \left[\frac{[1 - \alpha_e(\varphi_{\odot})] A_W}{\rho \Delta H_f} \int_{t \in d} I(d, \varphi_{\odot}, t) dt \right] \quad (11)$$

The meltwater production model of Eq. (9) and Eq. (10) is used to estimate the total meltwater volume in a melt season which is associated with the solar parameters $S(\varphi_{\odot})$ and $\alpha_e(\varphi_{\odot})$. Total solar-effect meltwater volume $\hat{V}_S(\varphi_{\odot})$ is calculated for values of the solar parameters over a range of values representing variability through a solar cycle. A differential meltwater volume attributable solely to the presumed UV forcing mechanism is produced, per Eq. (12):

$$\Delta V_{UV} = \hat{V}_S(\varphi_{\odot_{max}}) - \hat{V}_S(\varphi_{\odot_{min}}) \quad (12)$$

Under the presumed forcing mechanism, differential meltwater volume ΔV_{UV} accounts for a differential varve thickness observed between solar activity maximum and minimum. Meltwater is assumed to supply all of the differential sediment to the lake, i.e., aeolian and autochthonous sources are assumed to be negligible. Total sediment volume and seasonal differential meltwater volume then determine the average suspended sediment concentration (SSC) over the season that would be required to produce the differential varve thickness, as in Eq. (13):

$$\overline{SSC} = \frac{\bar{\rho}_{sed} \hat{A}_{sed} \Delta v_{thk}}{\Delta V_{UV}} \quad (13)$$

The dual UV phenomena are modeled to explore scenarios for solar forcing of varve thickness in the specific context of Iceberg Lake. Simulated seasonal meltwater volume is calculated for a range of parameter values representing variability through a solar cycle. Model parameter values used for simulations are given in Table 4.

Simulation results shown in Fig. 14a confirm the evident deduction that decreasing albedo leads to higher seasonal meltwater volume. Additionally, simulation results confirm that the change in solar constant over a solar cycle does not have an appreciable effect on total seasonal meltwater volume.

Mean sediment density and estimated lake area (Loso, 2009) are used to determine total sediment volume for a specified varve thickness. SSC is calculated for differential meltwater volume and the observed difference in varve thickness amplitude between solar maximum and minimum. Simulations indicate that a peak amplitude change of 1 W m^{-2} in broadband TSI has a negligible effect on meltwater volume and varve thickness. However, a $<5\%$ reduction in effective (broadband) albedo can produce a peak amplitude variation of 5-7 mm in varve thickness (Fig. 14b). Derived SSC values are comparable to observations from similar glacial environments (Haritashya et al., 2006).

Modeled seasonal meltwater volume due to solar activity represents between 10% and 35% of the lake's total estimated volume. Addition of convective meltwater would push the turnover into a typical range for a small proglacial setting. SSC values required to create a 10 mm varve are well within the range of observed values at glacial outwashes (Haritashya et al., 2006).

The model results are not intended to provide an accurate accounting of meltwater volume, sediment or SSC at Iceberg Lake, and additional field work would be required to attain such knowledge. However, the model indicates that glacial watershed SSC could be constant throughout a solar cycle and still produce observed changes in varve thickness; thus, the proposed dual UV effect can exclusively account for observed variation in varve thickness without invoking fundamental changes to any other aspects of the depositional process. Model results are robust to moderate perturbations in spectral albedo and insolation changes, particularly since a large SSC range would be compatible with values observed at other locations. Measurements of glacial outflow indicate that SSC correlates positively with flow rate (Haritashya et al., 2006), which was not invoked in the model, but which would allow further

flexibility in modeled albedo values. In particular, if SSC increases with flow rate, then a smaller decrease in albedo would be required to produce a given change in varve thickness.

5. DISCUSSION

Solar activity can, at most, account for ~12.08% (Eq. 8) of the total variability observed in the varve record; however, confirming even a small but direct solar-activity contribution to varve thickness is a significant result. A robust pink-noise process (Fig. 4) and various climate variables likely contribute significantly to the varve signal across a wide range of frequencies. The existence of multiple contributors to varve thickness variability does not eliminate the possibility that solar activity can have a direct influence on varve thickness.

Correlation between solar activity and varve thickness signals is a concomitant characteristic of direct forcing. To investigate correlation, use of most standard statistical measures of correlation is fatally compromised, since normality and stationarity assumptions of the signals are not met (Section 2.1). Significant correlation is established by randomization tests and bootstrapping simulations for several correlation measures. In every case, patterns observed in the varve thickness sequence observed at Iceberg Lake are not likely to be the result of a random response to the solar ‘forcing’ signal.

Correlation is not obvious in time-series plots of the raw data series (Figs. 1, 2). The hypothesized forcing is band-limited within the Schwabe frequency region, and spectral correlation is also a concomitant characteristic of direct forcing. Spectral methods are helpful for investigating linked relationships that may not be perceptible in time-series representations (Section 2.2). Corresponding features in the power spectra of both signals in the Schwabe region are indicative of cyclic co-variation (Figs. 4, 5). Intriguing patterns of pan-spectral covariation during periods of solar quiescence and solar activity crescendo are evident in the power

spectrograms (Fig. 6). Measures of cross-spectrum phase and coherence also indicate co-varying signals (Figs. 7, S-4).

Correlation between the two signals is a necessary condition, but not a sufficient condition for concluding a direct forcing relationship. Analogs of the HKE postulates for discerning causal relationships among correlated time-series records are applied to the varve and sunspot records. Every etiological assessment applied to the observed sunspot group number and Iceberg Lake varve thicknesses records is consistent with solar forcing at the Schwabe periodicity, and no clear contradiction of the cause-effect hypothesis is noted.

An epistemological basis for a direct solar activity influence on varve thickness is enhanced by identifying a physical process that could plausibly cause the hypothesized effect. Direct forcing could result from amplified ultraviolet (UV) emission during solar maxima, combined with lower UV albedo of glacial ice. Both phenomena have been previously reported in the literature. A (published) meltwater production model was modified to combine the dual, abetting UV phenomena, and implemented for the specific context of Iceberg Lake. Simulations confirm that the observed variation in broadband TSI over a solar cycle (with constant albedo) does not have an appreciable effect on total seasonal meltwater volume. Simulation results also confirm the evident deduction that changes in albedo (with constant spectral irradiance) have a linear effect on meltwater volume. Simulations that combine a decrease in UV albedo and an increase in UV irradiance indicate that a <5% reduction in effective albedo can produce a peak amplitude variation in varve thickness of 5-7 mm in the Iceberg Lake basin, as is observed in the measured sequence over a solar cycle.

Climate variables are known to influence varve thickness (e.g., Courtney Mustaphi and Gajewski, 2013; Thomas et al., 2012; Elbert et al., 2011; Larsen et al., 2011; Cook et al., 2009;

625 Thomas and Briner, 2009; Besonen et al., 2008; Bird et al., 2008; Moore et al., 2001; Gajewski
626 et al., 1997; Lotter and Birks, 1997). It is possible that solar activity is influencing some aspect
627 of climate, and it is the variation in climate that then drives changes in varve thickness.
628 Temperature, precipitation and wind-speed records in the region of Iceberg Lake do not display
629 time- or frequency-domain correlation with the sunspot record, diminishing the likelihood of a
630 forcing relationship. Still, other solar-activity-induced climate variability could plausibly affect
631 varve thickness, and the existence of any such connections remains an open question.
632 Connecting additional climate features to varve deposition requires two physical mechanisms:
633 solar activity effects on climate, then climate effects on varve deposition. The combination of
634 mechanisms must be capable of producing the observed changes in varve thickness.
635 Additionally, the envisioned climate variable would need to vary appropriately in the region of
636 Iceberg Lake in order to establish plausibility of an effect on varve thickness. Effects of solar-
637 activity-induced climate variability would also occur in conjunction with the direct solar activity
638 effect on varve thickness. Forcing analysis indicates that the direct dual UV effect is capable of
639 accounting completely for the observed magnitude of varve thickness variation through a solar
640 cycle. Thus, it would remain to be determined how multiple forcing mechanisms contribute to
641 the total variability in varve thickness.

642 A plausible depositional framework for solar and climate forcing of varved sediments
643 also lends credibility to interpretations of patterns observed in ancient rocks (Hughes et al., 2003;
644 Bracewell, 1988; Sonnet and Trebisky, 1986; Williams and Sonett, 1985), providing a context
645 for investigations into ancient solar variability. An STMEM spectrogram of the complete varve
646 thickness record at Iceberg Lake is shown in Fig. 15. Effects of the quiescent phase of solar
647 activity on varve thickness spanning the Maunder and Dalton minima appear to have begun in

the late 1300's CE, with a brief power pulse in the late 1500's CE. A similar pause may be expressed near 500 CE. Pink noise intensity of varve thickness is a consistent component through time, spanning the apparent solar lulls. The recent intensity of the Schwabe cycle effect on varve thickness is not expressed at any other point in the record.

Solar activity may represent a significant and perhaps underappreciated variable factor in energy budgets for some glaciers. Incorporating a direct solar radiation component has been shown to improve glacial meltwater predictions (Hock, 1999). Direct forcing of glacial meltwater volume by solar activity may contribute significantly to glacial retreat, and may account for persistently observed mass-balance deficits (Yong et al., 2007). The putative forcing mechanism would be pronounced at high latitudes and high elevations, where Earth's atmosphere absorbs less of the ultraviolet energy emitted by the Sun due to relatively thin and dry atmosphere. Periods of lowered ozone concentration near the poles lead to increased UV intensity at the surface (Smith et al., 1992). Processes that reduce polar ozone concentration would exacerbate a solar activity UV effect on glacial ice, suggesting a link between human activity and recent, accelerated polar ice cap melting.

6. SUMMARY

The primary objective of the preceding analysis is to assess the hypothesis that solar activity contributed directly to variations in varve thickness at Iceberg Lake within the Schwabe periodicity. The sum of evidence and arguments presented indicate it is probable that solar activity contributed directly to variations in varve thickness at Iceberg Lake within the Schwabe frequency band, without an intermediary solar effect on climate. A potential direct forcing mechanism is identified as increased UV irradiance during solar maxima resulting in reduced effective albedo of glacial ice, thereby modulating meltwater volume and sediment delivered to

the lake. Direct solar forcing of varve thickness provides a context for rhythmic patterns observed in ancient rocks that have been attributed to solar activity. The proposed UV forcing mechanism also suggests that a solar activity term may contribute new insight into glacier mass-balance theory.

Acknowledgments

We gratefully acknowledge support for this research from the STEM Teacher and Researcher (STAR) Program at California Polytechnic State University, San Luis Obispo, CA.

All data sets used for this study are available from the National Oceanic and Atmospheric Administration (NOAA). We are grateful for assistance from Bruce Bauer at NOAA National Centers for Environmental Information (NCEI, formerly the National Climatic Data Center (NCDC)).

We also wish to express our sincere gratitude to the anonymous reviewers for their reasoned and insightful comments, which lead to significant improvements in the paper.

References

- Amann, B., Szidat, S., and Grosjean, M., 2015. A millennial-long record of warm season precipitation and flood frequency for the North-western Alps inferred from varved lake sediments: implications for the future. *Quat. Sci. Rev.*, **115**, 89–100.
- Antoni, J., 2007. Cyclic spectral analysis in practice. *Mech. Syst. Sign. Proc.*, **21**, 597–630.
- Barnett, L. and Seth, A.K., 2014. The MVGC multivariate Granger causality toolbox: a new approach to Granger-causal inference. *J. Neurosci. Meth.*, **223**, 50–68.
- Besonen, M.R., Patridge, W., Bradley, R.S., Francus, P., Stoner, J.S., and Abbott, M.B., 2008. A record of climate over the last millennium based on varved lake sediments from the Canadian High Arctic. *The Holocene*, **18**(1), 169–180.
- Bird, B.W., Abbott, M.B., Finney, B.P., and Kutchko, B., 2008. A 2000-year varve-based climate record from the central Brooks Range, Alaska. *J. Paleolimnol.*, **41**(1), 25–41.
- Blass, A., Anselmetti, F.S. and Ariztegui, D., 2003. 60 years of glaciolacustrine sedimentation in Steinsee (Sustenpass, Switzerland) compared with historic events and instrumental meteorological data. In *Lake Systems from the Ice Age to Industrial Time* (pp. 59–71). Birkhäuser Basel.
- Bracewell, R.N., 1988. Spectral analysis of the Elatina series. *Sol. Phys.*, **116**(1), 179–194.
- Cook, T.L., Bradley, R.S., Stoner, J. S., and Francus, P., 2009. Five thousand years of sediment transfer in a high arctic watershed recorded in annually laminated sediments from Lower Murray Lake, Ellesmere Island, Nunavut, Canada. *J. Paleolimnol.*, **41**(1), 77–94.
- Courtney Mustaphi, C.J., and Gajewski, K., 2013. Holocene sediments from a coastal lake on northern Devon Island, Nunavut, Canada. *Can. J. Earth Sci.*, **50**(5), 564–575.
- Diedrich, K.E., and Loso, M.G., 2012. Transient impacts of Little Ice Age glacier expansion on sedimentation processes at glacier-dammed Iceberg Lake, southcentral Alaska. *J. Paleolimnol.*, **48**(1), 115–132.
- Durbin, J., and Watson, G.S., 1951. Testing for serial correlation in least squares regression II. *Biometrika*, **38**(1-2), 159–179.

- Elbert, J., Grosjean, M., von Gunten, L., Urrutia, R., Fischer, D., Wartenburger, R., Ariztegui, D., Fujak, M. and Hamann, Y., 2011. Quantitative high-resolution winter (JJA) precipitation reconstruction from varved sediments of Lago Plomo 47 S, Patagonian Andes, AD 1530–2002. *The Holocene*, **22**(4), 465–474.
- Evans, A.S., 1976. Causation and disease: the Henle-Koch postulates revisited. *Yale J. Biol. Med.*, **49**(2), 175–195.
- Fisher, R.A., 1936. *Statistical Methods for Research Workers*, 339 p. Available online, e.g., http://krishikosh.egranth.ac.in/bitstream/1/2048218/1/0039_2689A.pdf
- Fröhlich, C., and Lean, J., 2004. Solar radiative output and its variability: evidence and mechanisms. *Astron. Astrophys. Rev.*, **12**(4), 273–320.
- Gajewski, K.J., Hamilton, P., and McNeely, R., 1997. A high-resolution proxy-climate record from an arctic lake with annually-laminated sediments on Devon Island, Nunavut, Canada. *J. Paleolimnol.*, **17**, 215–225.
- Grenfell, T.C., and Perovich, D.K., 1984. Spectral albedos of sea ice and incident solar irradiance in the southern Beaufort Sea. *J. Geophys. Res.*, **89**(C3), 3573–3580.
- Haltia-Hovi, E., Saarinen, T., and Kukkonen, M., 2007. A 2000-year record of solar forcing on varved lake sediment in eastern Finland. *Quat. Sci. Rev.*, **26**(5-6), 678–689.
- Hanes, B. E., Fisher, T. G., Becker, R. H., and Martin-Hayden, J. M., 2014. Elucidating paleo dune activity and timing from wetlands in the lee of coastal sand dunes, Grand Mere Lakes, Michigan, USA. Geological Society of America Special Paper 508, pp. 133–149.
- Haritashya, U.K., Singh, P., Kumar, N., and Gupta, R.P., 2006. Suspended sediment from the Gangotri Glacier: Quantification, variability and associations with discharge and air temperature. *J. Hydrol.*, **321**(1), 116–130.
- Hathaway, D.H., Wilson, R.M., and Reichmann, E.J., 2002. Group sunspot numbers: sunspot cycle characteristics. *Sol. Phys.*, **211**(1-2), 357–370.
- Hesterberg, T., Moore, D. S., Monaghan, S., Clipson, A., and Epstein, R., 2005. Bootstrap methods and permutation tests. In: *Introduction to the Practice of Business Statistics*, W.H. Freeman and Co., New York, NY.
- Hock, R., 1999. A distributed temperature-index ice-and snowmelt model including potential direct solar radiation. *J. Glaciol.*, **45**(149), 101–111.
- Hodder, K.R., Gilbert, R., and Desloges, J.R., 2007. Glaciolacustrine varved sediment as an alpine hydroclimatic proxy. *J. Paleolimnol.*, **38**(3), 365–394.
- Hoyt, D.V., and Schatten, K.H., 1998. Group sunspot numbers: a new solar activity reconstruction. *Sol. Phys.*, **179**, 189–219.
- Hughes, G.B., 2017. *Frequency-Domain Analysis with DFTs*, SPIE Press, Inc., Bellingham, WA, 230 p. ISBN: 9781510616097.
- Hughes, G.B., Giegengack, R. and Kritikos, H.N., 2003. Modern spectral climate patterns in rhythmically deposited argillites of the Gowganda Formation (Early Proterozoic), southern Ontario, Canada. *Earth Planet. Sci. Lett.*, **207** (1), 13–22.
- Koch, R., 1891. Über bakteriologische Forschung Verhandlung des X Internationalen Medicinischen Congresses, Berlin, 1890, 1, 35. August Hirschwald, Berlin. (In German.) Xth International Congress of Medicine, Berlin.
- Kwiatkowski, D., Phillips, P.C.B., Schmidt, P., and Shin, Y., 1992. Testing the null hypothesis of stationarity against the alternative of a unit root, *J. Econometrics*, **54**(1–3), 159–178.

- Lamoureux, S.F., and Gilbert, R., 2004. A 750-yr record of autumn snowfall and temperature variability and winter storminess recorded in the varved sediments of Bear Lake, Devon Island, Arctic Canada. *Quat. Res.*, **61**(2), 134–147.
- Lamoureux, S.F., Gilbert, R., and Lewis, T., 2002. Lacustrine sedimentary environments in high arctic proglacial Bear Lake, Devon Island, Nanavut, Canada, *Arct. Antarct. Alp. Res.*, **34**(2), 130–141.
- Larsen, D.J., Miller, G.H., Geirsdóttir, Á., Thordarson, T., 2011. A 3000-year varved record of glacier activity and climate change from the proglacial lake Hvítárvatn. *Quat. Sci. Rev.*, **30**, 2715–2731.
- Lean, J.L., Rottman, G.J., Kyle, H.L., Woods, T.N., Hickey, J.R., and Puga, L.C., 1997. Detection and parameterization of variations in solar mid-and near-ultraviolet radiation (200–400 nm). *J. Geophys. Res.*, **102**(D25), 29939–29956.
- Lewis, T., Gilbert, R. and Lamoureux, S.F., 2002. Spatial and temporal changes in sedimentary processes at proglacial Bear Lake, Devon Island, Nanavut, Canada, *Arct. Antarct. Alp. Res.*, **34**(2), 119–129.
- Los0, M.G., 2009. Summer temperatures during the Medieval Warm Period and Little Ice Age inferred from varved proglacial lake sediments in southern Alaska. *J. Paleolimnol.*, **41**(1), 117–128.
- Lotter, A.F., and Birks, H.J.B., 1997. The separation of the influence of nutrients and climate on the varve time-series of Baldeggersee, Switzerland. *Aquat. Sci.*, **59**, 362–375.
- Malinka, A., Zege, E., Heygster, G., and Istomina, L., 2016. Reflective properties of white sea ice and snow. *The Cryosphere*, **10**(6), 2541–2557.
- Moore, J.J., Huguen, K.A., Miller, G.H., and Overpeck, J.T., 2001. Little Ice Age Recorded in Summer Temperatures from Varved Sediments of Donard Lake, Baffin Island, Canada. *J. Paleolimnol.*, **25**, 503–517.
- Nussbaumer, S.U., Steinhilber, F., Trachsel, M., Breitenmoser, P., Beer, J., Blass, A., Grosjean, M., Hafner, A., Holzhauser, H., Wanner, H., and Zumbühl, H.J., 2011. Alpine climate during the Holocene: a comparison between records of glaciers, lake sediments and solar activity. *J. Quat. Sci.*, **26**(7), 703–713.
- NIST Handbook 1.3.5.14, <https://www.itl.nist.gov/div898/handbook/eda/section3/eda35e.htm>.
- Ojala, A.E.K., Francus, P., Zolitschka, B., Besonen M., and Lamoureux, S.F., 2012. Characteristics of sedimentary varve chronologies—a review. *Quat. Sci. Rev.*, **43**, 45–60.
- Press, W.H., Teukolsky, S.A., Vetterling, W.T. and Flannery, B.P., 2007. *Numerical Recipes 3rd Edition: The Art of Scientific Computing*, Cambridge University Press New York, NY, USA, ISBN: 978-0521880688.
- Seth, A.K., Barrett, A.B. and Barnett, L., 2011. Causal density and integrated information as measures of conscious level. *Philos. T. Roy. Soc. A*, **369**(1952), 3748–3767.
- Smith, R.C., Prezelin, P.B., Baker, K.E.A., Bidigare, R.R., Boucher, N.P., Coley, T., Karentz, D., MacIntyre, S., Matlick, H.A., Menzies, D., and Ondrusek, M., 1992. Ozone depletion: ultraviolet radiation and phytoplankton biology in Antarctic waters. *Science*, **255**(5047), 952–959.
- Sonett, C.P. and Trebisky, T.J., 1986. Secular change in solar activity derived from ancient varves and the sunspot index. *Nature*, **322**(6080), 615–617.
- Stephens, M. A., 1974. EDF Statistics for Goodness of Fit and Some Comparisons, *J. Am. Stat. Assoc.*, **69**, 730–737.

- Svalgaard, L., and Schatten, K.H., 2016. Reconstruction of the sunspot group number: the backbone method. *Sol. Phys.*, **291**(9-10), 2653–2684.
- Thomas, E.K., McGrane, S., Briner, J.P., and Huang, Y., 2012. Leaf wax d2H and varve-thickness climate proxies from proglacial lake sediments, Baffin Island, Arctic Canada. *J. Paleolimnol.*, **48**(1), 193–207.
- Thomas, E.K., and Briner, J.P., 2009. Climate of the past millennium inferred from varved proglacial lake sediments on northeast Baffin Island, Arctic Canada. *J. Paleolimnol.*, **41**(1), 209–224.
- Vaughan, S., 2005. A simple test for periodic signals in red noise. *Astron. Astrophys.*, **431**(1), 391–403.
- Williams, G.E., and Sonett C.P., 1985. Solar signature in sedimentary cycles from the late Precambrian Elatina Formation, Australia. *Nature*, **318**(6046), 523–527.
- Willson, R.C., 1997. Total solar irradiance trend during solar cycles 21 and 22. *Science*, **77**(5334), 1963–1965.
- Willson, R.C., and Hudson, H.S., 1991. The Sun's luminosity over a complete solar cycle. *Nature*, **351**(6321), 42–44.
- Yong, Z., Shiyin, L., and Yongjian, D., 2007. Glacier meltwater and runoff modelling, Keqicar Baqi glacier, southwestern Tien Shan, China. *J. Glaciol.*, **53**(180), 91–98.
- Zolitschka, B., Francus, P., Ojala, A.E., and Schimmelmänn, A., 2015. Varves in lake sediments—a review. *Quat. Sci. Rev.*, **117**, 1–41.

823
824

Term	Interpretation	Units
$\hat{V}_{MS}$	Estimated total meltwater produced during a melt season	l
d	Day of year, within the melt season	--
MS	Melt season time domain (day of year boundaries)	--
$V_c(d)$	Meltwater volume produced by convectional heat transfer from the atmosphere on day of year d	l
$\alpha_e(\varphi_{\odot})$	Effective broadband albedo of the glacial ice surface	dimensionless
$\varphi_{\odot}$	Schwabe cycle phase	rad
$\hat{I}(\varphi_{\odot}, d, t)$	Estimated potential clear-sky insolation	W/m ²
t	Time of day (local mean time)	decimal hours
A_W	Effective surface area of the glacier ice-field watershed	m ²
ΔH_f	Latent heat of fusion of ice	J/g
ρ	Density of ice at 0°C	g/l

Table 1. Definition of forcing model terms in Eq. (9).

825
826

Term	Interpretation	Units
$\hat{I}(\varphi_{\odot}, d, t)$	Estimated potential clear-sky insolation	W/m ²
$S(\varphi_{\odot})$	Solar constant	W/m ²
$\frac{r_0}{r(d)}$	Eccentricity correction factor	dimensionless
$\bar{\psi}$	Mean atmospheric clear-sky transmissivity	dimensionless
P	Atmospheric pressure at location	Pa
P_0	Mean atmospheric pressure at sea level	Pa
$Z(t)$	Solar zenith angle	rad
β	Slope angle	rad
$\phi(t)$	Solar azimuth angle	rad
θ	Slope azimuth angle	rad

Table 2. Definition of forcing model terms in Eq (10).

Parameter	Value	Reference
$\alpha_e(\varphi_{\odot})$ (solar cycle range)	0.90-0.85	(Malinka et al., 2016)
$S(\varphi_{\odot})$ (solar cycle range)	1367-1368.5 W m ⁻²	(Fröhlich and Lean, 2004)
$\hat{A}_{sed}$ Lake sedimentation area	4.4 km ²	(Diedrich and Loso, 2012)
A_W Total watershed area	74 km ²	(Loso, 2009)
Proportion glacial watershed	52%	(Loso, 2009) (est. for 2009)
$\bar{\rho}_{sed}$ Mean sediment density	1170.9 kg/m ³	(Loso, 2009)
Location	60°46' N, 142°57' W	(Loso, 2009)
Elevation	933 m asl	(Loso, 2009)
ΔH_f (ice)	333.55 J/g	(accepted value)
P_0	101325 Pa	(accepted value)
P	$P_0 - 1200 \cdot \text{Elev. (m)}$	(from dry lapse rate)
Melt Season Days of Year	170-265	(selected baseline)
$\bar{\psi}$	0.85	(average value, est.)
$\bar{\beta}$	10°	(average value, est.)
$\bar{\theta}$	180°	(average value, est.)

Table 3. Meltwater model parameter values for Iceberg Lake simulation.

Figure 1. Average yearly sunspot group number, 1610-1995 CE (Hoyt and Schatten, 1998); data displayed as accessed from the NOAA NGDC repository. Shaded regions are the Maunder (1645-1715 CE) and Dalton (1796-1820 CE) minima.

Figure 2. Varve thickness sequence from Iceberg Lake, AK, 1610-1995 CE (Loso, 2009); data displayed as accessed from the NOAA NCEI repository. Shaded regions are Maunder (1645-1715 CE) and Dalton (1796-1820 CE) solar minima.

Figure 3. Varve thickness from Iceberg Lake, AK, and annual average sunspot group number, 1610-1995 CE ($n = 386$). Both raw signals were low-pass filtered, with cutoff frequency 0.125 cycles per year (8-year period), to visually highlight any potential correlation between the signals near the predominant (Schwabe) solar activity period.

Figure 4. (a) DFT peak amplitude spectrum of de-trended **(a)** sunspot group number and **(b)** varve thickness. Pink noise estimators are calculated using a spectral model (Eq. (2)); solid purple lines are best-fit model to data. Green lines are χ^2 95% $CV_{1,U}$ (Eq. (3)).

Figure 5. MEM power spectral density (non-normalized), calculated with 25 poles, at 500 frequencies.

Figure 6. STMEM power spectrograms ($\sigma = 20$ years), 1610-1995 CE. **(a)** Annual average group sunspot number. **(b)** Varve thickness record from Iceberg Lake, AK. Spectrograms produced from sequential MEM spectra.

Figure 7. (a) Cross-spectrum phase difference (as lag). Positive lag at the Schwabe periodicity indicates a sunspot-lead relationship, consistent with a solar forcing hypothesis. **(b)** Magnitude-squared coherence, indicating high correlation between the two signals within the relevant frequency band. A bootstrap 95% $CV_{1,U}$ for squared coherence at frequencies within the forcing frequency band is indicated.

Figure 8. (a) Sample CCSC for the varve and sunspot records. **(b)** CCSC at selected spectral frequencies, with the 99% upper confidence bound.

Figure 9. DFT peak amplitude spectra of **(a)** average daily maximum temperature and **(b)** average daily total rainfall from 10 stations in southeastern Alaska. Daily sampling gives a Nyquist cutoff of $f_c \approx 0.002738$ cycles/year in the DFT periodograms of these climate variables; the frequency axes in the plots are truncated for more direct comparison with the annually-sampled varve spectra ($f_c = 0.5$ cycles/year). Full DFT spectra are shown in Fig. S-3. Furthermore, the time span of the climate data (78.64 years) produces a periodogram bin width of ~ 0.0127 cycles/year; the varve and sunspot data (386 years) have bin width of ~ 0.00259 cycles/year, so the hypothesized forcing band spans more frequencies than in the climate spectra.

Figure 10 (a) DFT peak amplitude spectrum of varve-thickness record from Big Round Lake, Baffin Island, Canada. **(b)** MEM power spectral density (non-normalized) for the sunspot and Big Round Lake varve-thickness series (black) and the sunspot record (blue), calculated with 25 poles, at 500 frequencies.

Figure 11. (a) Seasonal meltwater volume as a function of effective (broadband) albedo. **(b)** SSC values that produce a 10 mm varve over the estimated area of Iceberg Lake, calculated from the modeled meltwater volume.

Figure 12. STMEM power spectrogram of the complete varve thickness record at Iceberg Lake, AK.

Figure 1. Average yearly sunspot group number, 1610-1995 CE (Hoyt and Schatten, 1998); data displayed as accessed from the NOAA NGDC repository. Shaded regions are the Maunder (1645-1715 CE) and Dalton (1796-1820 CE) minima.

Figure 2. Varve thickness sequence from Iceberg Lake, AK, 1610-1995 CE (Loso, 2009); data displayed as accessed from the NOAA NCEI repository. Shaded regions are Maunder (1645-1715 CE) and Dalton (1796-1820 CE) solar minima.

Figure 3. Varve thickness from Iceberg Lake, AK, and annual average sunspot group number, 1610-1995 CE ($n = 386$). Both raw signals were low-pass filtered, with cutoff frequency 0.125 cycles per year (8-year period), to visually highlight any potential correlation between the signals near the predominant (Schwabe) solar activity period.

Figure 4. (a) DFT peak amplitude spectrum of de-trended (a) sunspot group number and (b) varve thickness. Pink noise estimators are calculated using a spectral model (Eq. (2)); solid purple lines are best-fit model to data. Green lines are χ^2 95% $CV_{1,U}$ (Eq. (3)).

Figure 5. MEM power spectral density (non-normalized), calculated with 25 poles, at 500 frequencies.

Figure 6. STMEM power spectrograms ($\sigma = 20$ years), 1610-1995 CE. **(a)** Annual average group sunspot number. **(b)** Varve thickness record from Iceberg Lake, AK. Spectrograms produced from sequential MEM spectra.

Figure 7. (a) Cross-spectrum phase difference (as lag). Positive lag at the Schwabe periodicity indicates a sunspot-lead relationship, consistent with a solar forcing hypothesis. (b) Magnitude-squared coherence, indicating high correlation between the two signals within the relevant frequency band. A bootstrap 95% $CV_{1,U}$ for squared coherence at frequencies within the forcing frequency band is indicated.

Figure 8. (a) Sample CCSC for the varve and sunspot records. (b) CCSC at selected spectral frequencies, with the 99% upper confidence bound.

Figure 9. DFT peak amplitude spectra of (a) average daily maximum temperature and (b) average daily total rainfall from 10 stations in southeastern Alaska. Daily sampling gives a Nyquist cutoff of $f_c \approx 0.002738$ cycles/year in the DFT periodograms of these climate variables; the frequency axes in the plots are truncated for more direct comparison with the annually-sampled varve spectra ($f_c = 0.5$ cycles/year). Full DFT spectra are shown in Fig. S-3. Furthermore, the time span of the climate data (78.64 years) produces a periodogram bin width of ~ 0.0127 cycles/year; the varve and sunspot data (386 years) have bin width of ~ 0.00259 cycles/year, so the hypothesized forcing band spans more frequencies than in the climate spectra.

Figure 10 (a) DFT peak amplitude spectrum of varve-thickness record from Big Round Lake, Baffin Island, Canada. (b) MEM power spectral density (non-normalized) for the sunspot and Big Round Lake varve-thickness series (black) and the sunspot record (blue), calculated with 25 poles, at 500 frequencies.

Figure 11. (a) Seasonal meltwater volume as a function of effective (broadband) albedo. (b) SSC values that produce a 10 mm varve over the estimated area of Iceberg Lake, calculated from the modeled meltwater volume.

Figure 12. STMEM power spectrogram of the complete varve thickness record at Iceberg Lake, AK.

Draft

Solar Activity Expressed in a Modern Varve-Thickness Sequence

Gary B. Hughes^{1*}, Jordan Adams² and Jaclyn M.H. Cockburn³

¹Statistics Department, California Polytechnic State University, San Luis Obispo, CA 93407.

²Physics Department, California Polytechnic State University, San Luis Obispo, CA 93407.

³Geography Department, University of Guelph, 50 Stone Rd East, Guelph ON, N1G 2W1.

*Corresponding author: Gary Hughes (gbhughes@calpoly.edu)

Graphical Abstract: