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Effects of solar forcing and North Atlantic oscillation on the climate of continental Scandinavia during the Holocene

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ABSTRACT

10,000-year-long varved sediment records from lakes Nautajärvi and Korttajärvi, Finland provide evidence of climate and environment oscillations at multi-decadal to millennial timescales. We used two independent methods to extract periodic features from these time series of clastic laminae and assess their statistical reliability. Analyses revealed that seasonal sediment fluxes correspond to environmental changes with statistically significant periodicities of 1500–1800, 1000, 600–800, nearly 300, nearly 200, 150–170, nearly 90 and 47 years, showing variable coherency with different climate forcing factors and other palaeoproxy records in the Northern Hemisphere. Results indicate that the Holocene winter climate in continental Scandinavia was forced by a combination of several factors, at least by solar variability and the North Atlantic ocean–atmosphere circulation-patterns, with varying influences through time.

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1. Introduction

The reconstruction of natural climate changes prior to the industrial epoch is necessary for quantitative understanding of the magnitude and rapidity of ongoing climate change. An important part of this work is recognition of the characteristics and causes of natural cycles and trends that force climate variability on different timescales. The cyclic nature of the Earth's climate during the Holocene epoch is documented with instrumental, historical and proxy records (e.g. Eddy, 1976; Stuiver et al., 1991; Bull et al., 2000). Over longer time scales, the glacial cycles are driven by variations of the Earth's orbit (Milankovich cycles), which cause variations in the amount of solar radiation (insolation) reaching the Earth (Zachos et al., 2001). There is considerable evidence indicating that solar variability is also one of the primary reasons for natural cycles in Earth's climate at decadal to millennial time scales, some of which are amplified, dampened or delayed by complex feedback effects in the land–ocean–atmosphere systems (e.g. Lean, 2002; Burroughs, 2003).

The classical spectral analysis of time series is based on the periodogram, defined originally by Schuster (1898) as the discrete Fourier transform of the autocovariance sequence of the data. The periodogram, however, is an inconsistent estimator of the spectrum which has led to a multitude of variance reduction schemes, typically by smoothing the periodogram. Thomson (1990) gives a review of periodogram methods from the perspective of Holocene climate reconstructions. His conclusion is that " … for the analysis of Holocene climate data, the multiple data-window method of spectrum estimation is better than the various ad-hoc methods of time series analysis". The REDFIT program (Schulz and Mudelsee, 2002) computes a spectral estimate using Welch windowing coupled with the Lomb-Scargle periodogram (Lomb, 1976; Scargle, 1982). The Lomb-Scargle method estimates the spectrum by least-squares fitting of sine series. The advantage of this method is that, unlike the classical Fourier transform, it is applicable to time series which have uneven sampling. For time series with even sampling, the Lomb-Scargle method agrees with the Fourier transform. Ghil et al. (2002) gives a lengthy review of spectral methods for climatic time series, including methods such as SSA, Monte Carlo SSA, maximum entropy method (MEM) and the multitaper method (MTM). SSA (singular spectrum analysis), originating in the 1980's from the work of Broomhead and King (1986a, b), is a non-statistical, purely algebraic method, which lends itself to various

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purposes, such as enhancing the signal-to-noise ratio and separation of periodic phenomena. Wavelet methods, and similarly SSA, perform a time-domain analysis of data which, unlike the Fourier-based methods, provide time-localized information about the data. Wavelets and SSA have the advantage over Fourier-based methods that they can be applied to non-stationarity time series as well. Wavelets were originally introduced to geophysical applications with the analysis of seismic signals in the 1980's, since wavelets can capture local short-lived transient phenomena. For a review of wavelet methods in geophysics, see e.g. Kumar and Foufoula-Georgiou (1997). A recent monograph on climate time series analysis is given by Mudelsee (2014).

Climatic time series have typically excess spectral power at low frequencies, and as such the standard physically plausible background noise assumption is that of red (autoregressive AR(1)) noise. The REDFIT program handles the statistical inference by calculating the theoretical AR(1) spectrum confidence limits given that the data set contains only red noise. The basic SSA method is not well-suited for separation of signal from red noise, and as such the Monte Carlo SSA (Allen and Smith, 1996) was developed. As a recently developed alternative to Monte Carlo SSA, we employed the Posterior SSA method (Holmström and Launonen, 2013) which couples the SSA with Bayesian posterior modeling of the signal. For comparison to an established method, we performed the spectral analysis with the REDFIT program. We believe that the REDFIT as a frequency-domain and PSSA as a time-domain method complement each other and, in case they find similar features, bring robustness and added confidence to the results.

Studies of rhythmic sedimentation in depositional environments can contain information about the frequency and magnitude of past environmental change. The formation of varves (i.e. annually laminated sediments) are defined as sequences of sedimentary laminations deposited within a single year in glacial, lacustrine and marine environments (e.g. DeGeer, 1912; Zolitschka, 2007; Saarnisto and Ojala, 2009). The structure of varves varies in relation to changes in the sedimentary environment, typically seen as changes either in lamina thickness or varve components, or both. Because of their precise and continuous timescale (varve chronology) and the response of their physical characteristics to environmental change, scientists have widely used varves in palaeoclimate reconstruction (e.g. Kaufman et al., 2009; Mann et al., 2009; Shi et al., 2013). Furthermore, being able to record the prominent features of changes with seasonal resolution, varved sediments are intriguing proxy records to understand and quantify the influence of external forcing on lacustrine sedimentation. By definition, a series of varves is a regular time series that can be densely sampled, even at sub-annual scale, to provide information about past environmental change that does not rely on age-depth modeling and interpolation between unevenly dated levels (e.g. Birks, 2008).

However, varved sediments are known to contain inhomogeneities due to factors such as basin evolution and typical errors of ±2% in varved chronologies (Ojala et al., 2012). Moreover, many records of inhabited areas have also been influenced by local land use during past decades or centuries and thus contain an anthropogenic component superimposed on natural variability (e.g. Andersen et al., 1995; Zolitschka, 1996; Lotter and Birks, 1997; Ojala and Alenius, 2005). Such site-specific inhomogeneities often lead to a lack of high-resolution (annual) site-to-site correlation, even between closely situated lakes that accumulate similar types of varves, as shown by Gälman et al. (2006) in northern Sweden. Their general explanation for this deviation was differences in lake catchment-size, catchment-to-lake fluxes, lake productivity and the influence of land use. Despite these cultural and local impacts on varve formation, the comparison of varved sequences on longer timescales is important when natural variance and periodic features in climate and environmental change are assessed. To overcome these site-specific challenges and still be able to use the seasonal-resolution data from sediment records of lakes Nautajärvi and Korttajärvi in Finland, we deciphered periodic features of their varved datasets and highlighted the observed features and anomalies with regard to cold and snowy winters in continental Scandinavia. The purpose of the present study was to determine dominant periodic characteristics of sedimentation in these lakes and to examine which periodicities are shared between both sites, which are currently exposed to a comparable regional climate and have sediments composed of a similar type of clastic-biogenic varves. Here, we discuss possible reasons for the observed periodicities, external forcing mechanisms affecting sedimentation and variations in laminae thickness, and the potential of using clastic-biogenic varves in characterizing the cyclicities of Holocene climate and environmental change in continental Scandinavia.

2. Study sites and varve data

Lakes Nautajärvi (NJ) and Korttajärvi (KJ) are located in the Fennoscandian boreal forest zone in central-southern Finland (Fig. 1, Table 1). The northern location and heat transport via the Gulf Stream and westerly winds are prominent climatic factors in this area. Presently, the mean annual temperature of the sites is ca +3 °C and the coldest and warmest months are normally January to February (−1 to −17 °C) and June to July (+12 to +17 °C), respectively. The mean annual sum of precipitation varies between 500 and 700 mm, with approximately one-third falling as snow. The catchment of both lakes consists of easily erodible fine-grained clastic material, with glacial till and bedrock outcrops in relative equal proportions. Both lakes contain oval-shaped basins that are supplied by river inflow and that effectively trap much of the sedimentary material, thus maintaining a fairly high rate (0.5–2.0 mm yr^{-1}) of continuous sedimentation.

Strong seasonal contrasts with several months of winter ice cover, spring floods, as well as summer and winter stratification of the water column (dimictic) are the main causes for the presence of clastic-biogenic varves in NJ and KJ (e.g. Ojala et al., 2000; Ojala et al., 2013). Varves extend uninterruptedly from the present day to 9852 ± 99 cal BP (7902 BC) in NJ and to 9540 ± 95 cal BP (7590 BC) in KJ, both characterized by a varve counting error of ±1% (Ojala and Tiljander, 2003). The digital documentation and detailed physical properties of varves have been presented in Tiljander et al. (2002), Ojala and Francus (2002) and Ojala and Tiljander (2003). Ojala and Alenius (2005) established the seasonal datasets and palaeoclimate interpretations based on the physical properties of the NJ varves, which they later combined with pollen-based temperature reconstructions (Giesecke et al., 2008; Ojala et al., 2008a). The varve data from KJ were thoroughly interpreted by Tiljander et al. (2003) for the last 3000 years, whereas the earlier ca 6600 years of the record (2940–9540 cal BP) were only briefly characterized by Tiljander et al. (2006). Neither of these time series has thus far been thoroughly analyzed for periodic features.

More recently, using sediment trap monitoring in NJ, Ojala et al. (2013) demonstrated that clastic-biogenic varves indeed reflect the annual deposition cycle of allochthonous inorganic material (clastic laminae) and organic remains, which are mostly of autochthonous origin (biogenic laminae). They were able to document that seasonal sediment fluxes generating the varves correspond with environmental changes, and that the clastic part of a varve varies more substantially than the biogenic part, thus providing a more sensitive proxy for past environmental and

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