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Evolution of NAO and AMO strength and cyclicity derived from a 3-ka varve-thickness record from Iceland

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ABSTRACT

A 3000-year varve-thickness record from Hvítárvatn, a glacier-dominated lake in central Iceland, preserves inter-annual variations in the delivery of glacially eroded sediment to the lake. The first-order low-frequency trend in varve thickness reflects increased glacial erosion through the Late Holocene, reaching a peak during the Little Ice Age (LIA). Superimposed on this trend are large inter-annual to decadal fluctuations in varve thickness that we suggest reflect variability in climate parameters that determine the efficiency of the fluvial transport system to deliver glacially eroded sediment to the lake each year. We use spectral analysis to test whether regular high-frequency cyclicity in varve thickness exists in the 3-ka record after removing the low-frequency variability. Spectral analyses from three sediment cores recovered from the lake show essentially the same periods of 2.8–3.4, 13, 35–40 and 85–93, for the overlapping ~900-year period. Additionally, cycles of 55, 130 and 290 years are found in the spectrum for the 3000-year record that do not show up in the spectra for the shorter cores. Some of these cycles show similar variability to those of the North Atlantic Oscillation (NAO) and Atlantic Multidecadal Oscillation (AMO). This relationship is supported by a significant correlation between varve thickness and both the NAO (precipitation) and AMO (summer temperature) indices over the 180-year instrumental period. NAO cyclicities (2–15 years) are weakly expressed in the first half of the record, increase between 600 and 1000 AD, decrease in strength during medieval time, and are most strongly expressed between 1300 AD and the early 20th century. AMO cyclicities (50 to 130 years) are also relatively weak in the first half of the record, becoming quite strong between 600 and 1000 AD and again between 1100 and 1500 AD, but are essentially absent through the peak of the LIA, between 1500 and 1900 AD, a time when strong cyclicities of about 35 years appear.

1. Introduction

Warming at high northern latitudes has increased in recent decades and has been shown to be greater than at lower latitudes (IPCC, 2007). Warming has already resulted in significant changes in the Arctic environment, including reduced sea ice cover, rapidly retreating glaciers, increased ocean temperatures, lengthening of snow-free season and thawing permafrost. Decadal-scale climate variability related to internal modes of variability may also play an important role in explaining recent warming (Zhang et al., 2007). High-resolution proxy data that can be used to reconstruct climate variability through time are essential in order to compare the present Arctic amplification to previous times, and to distinguish between natural variability and anthropogenic forcings, especially low-frequency natural variability that cannot be assessed with the relatively short instrumental record. Annually laminated (varved) lake sediment records from proglacial or ice-contact lakes are ideal archives for paleoclimate reconstructions. In addition to their annually resolved nature, such records offer the possibility to use changes in varve thickness as a climate proxy. A typical clastic varve consists of two primary layers: a relatively thick layer of silt and sand, which forms in the spring and summer during the melt season, and a thinner layer of clay deposited in winter when the lake is ice-covered. Thicker varves are the result of increased annual production of sediment and/or increased delivery of eroded sediment to the lake. On short timescales varve thickness may be related to changes in temperature and/or precipitation during the melt season that influence the efficiency of the fluvial transport systems (Ohlendorf et al., 1997; Blass et al., 2007; Bird et al., 2009;

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Cook et al., 2009; Loso, 2009; Thomas and Briner, 2009; Larsen et al., 2011), whereas on centennial timescales changes in varve thickness reflect changes in glacier size (Desloges and Gilbert, 1994; Leonard, 1997; Ohlendorf et al., 1997; Hodder et al., 2007; Tomkins et al., 2008).

Recently, interest has been growing to recover high-resolution Holocene paleoclimate records that preserve cyclicities of high-frequency variability that can assist forecasts of future climate change (Burroughs, 2003; Weedon, 2003). In addition, such high-resolution records may allow separation of natural climatic variability from a range of anthropogenic forcings.

Located at the boundary between the relatively warm, saline Atlantic current and the colder, low-salinity current from the Arctic Ocean, Iceland is ideally situated to reconstruct high-frequency variability in ocean currents, atmospheric dynamics, and the interactions between ocean and atmosphere in the past. The climate in Iceland is sensitive to changes in storm tracks, and is strongly affected by the Icelandic Low, a semi-permanent low-pressure centre which forms one pole of the North Atlantic Oscillation (NAO; Hurrell et al., 2003). In addition, the unique geological position of Iceland on the North Atlantic ridge results in frequent volcanic eruptions creating numerous tephra layers that are preserved in lake sediments and serve as precisely dated horizons during the historical period that constrain sedimentation age models.

Here we present spectral analyses of a 3000-year-long varved sediment record from Hvítárvatn (Larsen et al., 2011), a glacier-dominated lake in central Iceland. Meltwater streams draining the ice cap deliver glacially eroded sediment to the lake, with centennial-scale changes in sedimentation rate controlled by the overall erosive power of Langjökull, the second-largest ice cap in Iceland. The aim of this paper is to test whether coherent inter-annual to decadal variations are superimposed on the longer term trends in the varve-thickness record. A meteorological record covering the last ~50 years from Hveravellir, a nearby weather station, is spliced to the much longer Stykkishólmur record to develop a ~200-year instrumental record used to test correlations between varve thickness and specific climate variables. Spectral analysis is used to determine whether high-frequency variations in the varve record show regular periodicities, and if so, whether the cycles change over time, and to evaluate possible connections to known modes of natural variability.

2. Regional setting

Sediment delivery to Hvítárvatn (Fig. 1a; elev. 422 m asl, area 28.9 km^2, max. depth 83 m) is dominated by meltwater from Langjökull; in addition, two Langjökull outlet glaciers, Norðurjökull and Suðurjökull, terminated in the lake during the Little Ice Age (LIA; Fig. 1b; Geirsdóttir et al., 2008; Larsen et al., 2011).Varve thickness is controlled by the sediment flux to the lake and reflects changes in the erosive power of Langjökull (directly proportional to ice cap size), modulated by shorter-term fluctuations in the efficiency of the subglacial hydrologic system to deliver the eroded sediment to the lake.

3. Materials and methods

Here we focus on the higher frequency variations in varve-thickness that are expected to reflect the modes of variability on decade to century timescales. The varve records used in this paper were measured in sediment cores obtained from the northern basin of Hvítárvatn (Fig. 1b; Table 1). Varves have been counted and varve thickness measured from three separate core sites (HVT03-1, HVT03-2 and HVT03-3; Larsen et al., 2011). The annual nature of the laminae was confirmed using tephrochronology and cross-correlation on distinctive tephra and laminae patterns contained in the three sediment cores (Larsen et al., 2011). The longest varve record comes from HVT03-2, where the varves have been counted and measured for the past 3000 years. The varve records from the two other cores (HVT03-1 and HVT03-3) have been measured for the past ~1000 years. Here we use all three cores to compare their spectra for the overlapping period and to test the regional coherence of the varve thickness records. HVT03-2 and HVT03-3were recovered from a hyaloclastite ridge, over which 15 m of sediment has accumulated since deglaciation, with no indication of disturbances. Because the flat-topped ridge lies ~10 m above the adjacent lake floor, sedimentation is dominantly from suspension settling, avoiding complicating effects from sediment density flows that affect the main lake floor. The thickness of each annual lamina from these cores more accurately represents the annual sediment flux to the lake than would varves from cores recovered from the central deep. In contrast, core HVT03-1 is from the main basin, providing a test of the extent to which varve thickness depends on sedimentation regime.

All three cores are undisturbed, and nearly complete, with relatively few missing years (Table 1). At each site, twin cores with 3-m drives but offset by 1.5 m were recovered, allowing nearly all core breaks to be filled by the twin core (Larsen et al., 2011). The few remaining missing values were estimated with a linear interpolation to obtain a continuous record. Interpolation usually increases the autocorrelation in the time series which can bring in an extra bias to the power spectrum estimation (Mudelsee, 2010). However, this uncertainty is minimal in our case due to relatively few values estimated by interpolation. The sampling interval in all three cores is 1 year, so according to the Nyquist frequency ($1/2 \times$ sampling interval), the shortest cycle that can be obtained from the time series has a length of 2 years, although the significance of cycles containing fewer than 4 data points per oscillation are viewed with caution.

We use spectral analysis to determine whether there are regular high-frequency cyclicities in varve thickness over the past ~3 ka. Singular Spectrum Analysis (SSA; Vautard and Ghil, 1989) and Multi-Taper Method (MTM; Thomson, 1982) in kSpectra 2.13 Toolkit (spectraworks.com) were used to identify the significant periodicities in the time series. SSA is one of many methods of spectral analysis that is suitable for decomposing a time series into a (non-linear) trend, oscillatory components and noise (Ghil et al., 2002). Because our objective was to explore the potential climate significance of the high-frequency signal in the varve-thickness, we filtered out the low-frequency components prior to spectral analyses to prevent the results from being overwhelmed by the low-frequency signals. Due to the non-linear behaviour of the low-frequency signals, the common detrending method of subtracting a linear least squares regression line from the data is inappropriate. SSA was used to filter out non-linear components with periods that are long relative to the length of the time series. The embedded dimension used in the SSA analysis was $M = 100$ for the short time series and $M = 298$ for the longer one, based on the number of data points and the oscillations under investigation. The covariance matrix is calculated with the V&G method (Vautard and Ghil, 1989) and the Monte Carlo test was used where the error bars represent 95% of the variance.

The MTM was used to test for significant periodicities within the time series after the low-frequency components had been filtered out with SSA. MTM uses small sets of tapers to reduce the variance of the spectral estimates (Thomson, 1982). This method estimates a power spectrum with small bias, good smoothing, and yet high resolution, and is the preferred method to estimate spectra for evenly spaced time series. The MTM power spectra were calculated with 5 tapers and a bandwidth of 3 for the overlapping period of