Organic lacustrine sediment varves as indicators of past precipitation changes: a 3,000-year climate record from Central Finland

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Abstract

Annually laminated (varved) sediments from Lake Kallio-Kourujärvi, Central Finland, provide high-resolution sedimentological data for the last three millennia. These varves consist of two laminae that represent i) deposition during the spring-to-autumn growing season, composed of degraded organic matter and a variety of microfossils, and ii) deposition during winter, composed of fine-grained homogenous organic matter. Because of the absence of a clastic lamina, these varves differ from the typical, well-described, clastic-organic varve sequences in Fennoscandian lakes. Such organic varves in Finnish lakes have not been studied in detail before. Three thousand varves were counted and their seasonal deposition was distinguished. Comparison of varve thickness with meteorological data revealed a positive correlation between organic varve thickness and precipitation. This suggests that catchment erosion processes and consequent organic matter and nutrient inputs are important factors in organic varve formation. The correlation between temperature and growing-season lamina thickness varied from insignificant, to positive, to negative during different time spans. This suggests that organic matter accumulation can sometimes have a significant, but unpredictable role in organic varve formation, via organic matter production and degradation, processes that are influenced strongly by water column temperature. The organic varves of Lake Kallio-Kourujärvi enable a unique, high-resolution approach for the study of past climate and environment. Our results suggest that decadal periods of increased precipitation occurred during BP 2150-2090, 1710-1620, 1410-1360, 920-870 (1030-1080 AD), and after 370 BP (1580 AD). Dryer intervals occurred during BP 2750-2720, 1900-1850, 1800-1740, 1600-1500, and 780-700 (1170-1250 AD), 590-520 (1360-1430 AD).

Introduction

Annually laminated (varved) lake sediments reflect past climate and environmental changes (Dean et al. 2002; Brauer 2004; Haltia-Hovi et al. 2007; Ojala et al. 2008). In a boreal climate setting, characterized by snowy winters and mild summers, clastic-organic varves are commonly preserved in the sediment record. Many such records from Scandinavia have been studied in detail (Petterson et al. 1993; Itkonen and Salonen 1994; Snowball et al. 1999; Tiljander et al. 2003; Ojala and Alenius 2005; Haltia-Hovi et al. 2007). In these studies, the deposition of the clastic laminae was attributed to catchment erosion caused by snowmelt, whereas there was little discussion of organic laminae.

Organic laminae, consisting of various microfossils and fine-grained, amorphous organic matter are described from different varve types in diverse climate zones (O’Sullivan 1983; Anderson and Dean 1988; Bradbury 1988; Zolitschka 1998; Dean et al. 1999; Tiljander et al. 2003; Ojala and Alenius 2005; Haltia-Hovi et al. 2007; Chutko and Lamoureux 2009; Koutsodendris et al. 2011; Zahrer et al. 2013). Their thickness, however, has been under-utilized for paleoclimatological or paleoenvironmental reconstructions. The less frequent use of organic laminae for paleoclimatological reconstruction may be attributed to the fact that less is known about their formation, making interpretation potentially difficult.

Organic matter in varve structures comes from autochthonous, lacustrine productivity and allochthonous influx of material from the catchment (Meyers and Lallier-Vergès 1999). Productivity in lakes depends on multiple variables such as temperature, which defines the length of the growing season and controls the duration of spring and fall overturns, light, and precipitation, which partly controls nutrient availability (Bradbury 1988; Meyers and Ishiwatari 1993). Allochthonous organic material is transported to lakes via surface runoff and input streams, which carry particulate matter and humic substances from surrounding forests and mires. Net organic sediment accumulation, however, depends not only on primary production and influx, but also on organic carbon (OC) mineralization (Sobek et al. 2009; Gudasz et al. 2010), which is related to degradation of material in the water column (den Heyer and Kalff 1998), chemical composition of the organic matter, sediment accumulation rate, oxygen exposure time (Maerki et al. 2009) and bottom-water oxygen concentration, activity of microbial decomposers and mixing by macrobenthos (Hedges et al. 1999; Sobek et al. 2009). These variables are at least partly dependent on light and air temperature, which control water-column temperature and the timing and duration of water-column circulation.

Organic lamina thickness in boreal settings has been partly related to growing-season temperature (Itkonen and Salonen 1994; Tiljander et al. 2003; Ojala and Alenius 2005; Haltia-Hovi et al. 2007), but there is no consistent interpretation of the interactions between temperature and organic lamina thickness. A few studies on organic varves in the High Arctic (Chutko and Lamoureux 2009) and Central Europe (Koutsodendris et al. 2011), however, suggested they had high potential for paleoclimatological and geochemical studies.

Here we present an organic varve record from Lake Kallio-Kourujärvi, Central Finland. We used the record to investigate the suitability of organic varves for paleoclimate reconstructions and to better understand the interactions between climate conditions and organic matter accumulation. We shed light on climate variations and environmental changes during the past 3,000 years using variations in organic varve thickness. Human land-use effects in this remote location were minimal until very recently, and thus this lake sediment record provides reliable information about the late Holocene climate and environmental history of Central Finland.

Site description

Lake Kallio-Kourujärvi is located at 62° 33.655’N and 27° 0.373’E in the municipality of Suonenjoki in Central Finland, at an altitude of 117.2 m asl. It is an elongate lake with a surface area of 0.13 km^2 and a drainage area of approximately 10 km^2. Kallio-Kourujärvi is a mesotrophic, dimictic water body situated in the Southern Boreal vegetation zone where pine trees dominate the forests (Ruuhijärvi 1988). The deepest basin is located in the northern part of the lake and has a maximum water depth of 11 m (Fig. 1). There are two inlets into the southern bay and one at the western shore, and an outlet in the north. The lake is surrounded by forests and mires and has steep slopes to the east. The catchment is composed of Quaternary till, sand, *Carex* and *Sphagnum* peat and bedrock outcrops (Kukkonen and Leino 1985, 1989). Bedrock in the catchment is composed mainly of plutonic rocks such as granites (Pääjärvi 2000). There are no permanent human settlements in the vicinity of the lake.

Lake Kallio-Kourujärvi was formed after the retreat of the Weichselian ice sheet about 10,000 years ago (Eronen and Haila 1990). At that time, the lake and parts of the catchment were submerged by melt water. Because of its elevated location, Kallio-Kourujärvi was isolated at an early stage of the ice sheet retreat, although the exact timing of deglaciation is still unknown (Eronen and Haila 1990).

The annual mean temperature in the study area is approximately 2°C (Helminen 1987). The mean temperature of the coldest month (January) is –9°C and the mean temperature of the warmest month (July) is +16°C (Fig. 2). Annual precipitation is between 650 and 700 mm, of which about 40% falls as snow. Stable snow cover is usually present from the end of November until the end of April (Solantie 1987), whereas the lake is ice-covered somewhat longer and usually does not thaw until May (Kuusisto 1986).

Materials and methods

Coring

Lake Kallio-Kourujärvi was cored from the ice in the winters of 2008 and 2010, with a rod-operated piston-corer. Cores were collected in the deepest part of the lake where the water depth was 11.0 m. Two 6.4-cm-diameter cores, KKJ-2 (2008) and KKJ-3 (2010) were obtained (Fig. 1) within several meters of one another, as determined by GPS. About 400 cm (KKJ-2) and 200 cm (KKJ-3) of sediment were recovered at the sites. The KKJ-2 core was split into two parts for transport. A Limnos sampler (Kansanen et al. 1991) was used to obtain undisturbed near-surface samples using the mini ice finger technique (Saarinen and Wenho 2005). Three 25-cm-long mini ice finger cores were used to tie the varve chronology to the present day. Varve data from the last 3,000 years (140 cm) were available for this study.

Core sampling and thin section preparation

The sediment cores were opened carefully with a circular saw and a knife in the laboratory. The core was split in half lengthwise with a thin wire and the exposed fresh sediment surface was cleaned with a glass blade. Subsamples for thin section preparation were taken from core KKJ-2 in the manner described by Haltia-Hovi et al. (2007) and Lamoureux (1994). The sediment sequence was subsampled continuously for sediment embedding, using 11-cm-long aluminum molds with 1.5-cm overlap.

Subsamples were impregnated with Spurr low-viscosity epoxy resin, following the water-acetone-epoxy exchange method (Lamoureux 1994; Tiljander et al. 2002). Before impregnation, adequate dehydration was ensured by measuring the water content of the acetone (<0.5%) enthalpimetrically. For the first two epoxy-resin baths, a small amount of acetone was added to improve impregnation (Pike and Kemp 1996). Thin sections (15 x 110 mm) with a thickness of about 30 μm were prepared from the impregnated subsamples at the Helmholtz Centre Potsdam (German Research Centre for Geosciences), following the technique of Lotter and Lemcke (1999).

Varve counting and microfacies analysis

Varve analysis was performed along a line on the thin sections, using a stereomicroscope (Nikon SMZ800). Dark field illumination and 6x magnification were used. Two main laminae types were distinguished: 1) growing season lamina (GSL) and 2) winter lamina (WL), and their thickness was measured along a line drawn along the thin section (Table 1). The chronology from core KKJ-2 was tied to present day by linking similar varve patterns of KKJ-2 with the mini-ice-finger sample that had an intact sediment-water interface.

Magnetic measurements and chemical analysis

Low-field magnetic susceptibility (κ_{LF}, SI x 10^{-6}) was measured at 2.0-mm intervals, along the cleaned sediment surfaces of freshly opened cores (KKJ-2A, KKJ-3) that were covered with a thin plastic film. Measurements were done with an automatic measuring track and a Bartington MS2 susceptibility meter, coupled with a MS2E1 spot-reading sensor. Magnetic susceptibility measurements were used to correlate the two cores.

Paleomagnetic sample boxes (external dimensions 2.2 x 2.2 x 1.8 cm, volume 6.1 cm^3) were used to take samples for paleomagnetic measurements from core KKJ-3, at 3-cm intervals. A Molspin portable Minispin spinner magnetometer was used to measure the natural remanent magnetization (NRM). Magnetic inclination and relative declination were calculated from the NRM data. The core was oriented only for the z-axis, and thus results are relative declination. Paleomagnetic measurements were undertaken to evaluate the fidelity of the varve chronology.

The ratio of carbon to nitrogen (C/N) was measured on dried, homogenized samples, each weighing 5 mg. Samples were obtained from core KKJ-3 at 9-cm intervals. Measurements were made with an SIR-MS/CNS gas chromatography mass spectrometer in the accredited commercial Ambiotica Laboratory at the University of Jyväskylä. C/N ratio was analyzed to infer the provenance of the organic matter.

Statistical analyses

Correlations between total varve thickness (TOT), growing season varve thickness (GSL), and climate variables total annual precipitation (P_{ann}), growing season precipitation (P_{gs}) and temperature of the growing season (T_{gs}), were determined (Table 1). Meteorological data for the last 110 years (NORDKLIM) are from the Jyväskylä meteorological station, 75 km southwest of Lake Kallio-Kourujärvi (Fig. 1). We used the R 2.14.1 program (R Development Core Team 2011) for statistical analyses.

Pearson's correlation analyses were performed on combinations between the dependent (TOT, GSL) and independent (P_{ann}, P_{gs}, T_{gs}) variables for all possible time intervals. The Shapiro-Wilk or Kolmogorov-Smirnov normality tests were used to test the normal distribution of samples. If sample size was ≤50 years, the Shapiro-Wilk test was applied. Otherwise, the Kolmogorov-Smirnov test was used. If at least one variable was not normally distributed in a time period, Spearman's correlation analysis was used instead of Pearson's. Statistically significant ($p<0.05$) correlations, with the highest absolute values in a period ≥10 years, were observed in the data.

Results

Sediment description

Fresh sediment from Lake Kallio-Kourujärvi is black and varves are not visible with the naked eye. Varve structures become visible only when the sediment surface oxidizes. C/N ratios vary between 19 and 22.

The laminae are mainly of two types (Fig. 2). The varve year begins with a lamina that consists of highly degraded, massive organic matter, deposited during the growing season and ice-free period (GSL). Microfossils such as insect remains, chrysophyte cysts, sponge spicules, plant remains, pollen and diatoms are frequent. Dominant diatom species belong to the genus *Aulacoseira*, and diatoms of the genera *Cyclotella*, *Tabellaria*, *Eunotia*, *Pinnularia*, and *Suriella* are common. Layers of spring-blooming diatoms were not observed. Instead, diatoms are evenly distributed throughout the GSL. The other type of lamina represents deposition during winter (WL), and consists of homogenous, fine-grained organic material that has settled in quiet waters under ice cover (Tiljander et al. 2003).

Minerogenic laminae (ML) are common in the sediment of boreal lakes as a consequence of increased erosion induced by spring snowmelt floods (Ojala and Alenius 2005; Haltia-Hovi et al. 2007). In the Lake Kallio-Kourujärvi sediments, these laminae are 0.15 mm thick at maximum and occur only occasionally between WL and GSL in the top 9 cm of the record. Clay-size, minerogenic detritus is a minor component of GSL.

Varve variables and statistical analyses

The sediment of Lake Kallio-Kourujärvi is annually laminated up to the present, as observed in the thin sections and ice finger samples. Three variables in the varve structure were measured (Table 1): GSL, WL and TOT thickness. Varve boundaries were identified based on their microstructure. Although there is a gradual transition from GSL to WL, the boundary between WL and the overlying GSL is sharp. Sediment displaying a transition to lower numbers of microfossils was considered to belong to the GSL (Fig. 2) and only the homogenous organic layer was included in the measure of WL. Minerogenic laminae (ML) were not studied in detail because of their rare occurrence and very small thickness. The ML are, however, a component of total varve thicknesses.

The thickness of GSL ranges from 0.1 to 1.7 mm (Table 2), whereas WL are thinner, varying from 0.05 to 1.0 mm. All varve variables in the topmost sediment increase towards the present day. Other high-thickness values in GSL occur around BP 2150-2090, 1710-1620, 1410-1360 and 920-870, and after 370 (Fig. 3), and in WL around BP 2110-2080, 1660-1620, 1400-1370, 460-440 and since 50 (Fig. 3).

The varve thickness record shows periods of large-amplitude fluctuations that coincide with the thickest GSL (Fig. 3). There are large-amplitude variations during BP 1720-850, which indicate large inter-annual differences. At BP 850 there is a sudden decrease in variability, and this notably stable interval lasts until BP 700. Since BP 370, variability of varve thickness slowly increases toward the present.

The correlation between TOT thickness and P_{ann}, and GSL and P_{gs} for the time span of the last 110 years is generally positive, whereas the correlation between GSL thickness and T_{gs} is low and slightly negative. Statistical analyses show periods of both high positive and high negative correlation between these variables (Table 3).

Paleosecular variation and low-field magnetic susceptibility

Magnetic susceptibility was used to correlate cores KKJ-2A and KKJ-3 (Fig. 4). The values decrease toward the present, except for an increase in the topmost 7 cm (Fig. 4). Paleosecular variations (PSV) from lake Kallio-Kourujärvi were compared with PSV data from Lakes Nautajärvi (Fig. 1), Lehmilampi and Kortejärvi, where the major declination and inclination shifts were well dated (Ojala and Saarinen 2002; Haltia-Hovi et al. 2010). The most prominent inclination and relative declination shifts are generally recognized features (Haltia-Hovi et al. 2010; Snowball et al 1999; Turner and Thompson 1981) and referred following the nomenclature by Turner and Thompson (1981). Inclination features γ, δ, ε^1, and declination features e and f are clear and shift simultaneously in PSV data from Lake Kallio-Kourujärvi (Fig. 5), but declination feature d is not clearly recognized. This may be an artifact of core rotation during coring or opening of the core, but it may be that the feature is simply lacking in the record. Similarity of PSV data to records from nearby, well-dated lake sequences supports the reliability of the Kallio-Kourujärvi chronology.

Chronology and error estimation

The chronology was tied to present using marker varve horizons in the mini ice finger samples from the sediment-water interface cores and in thin sections from core KKJ-2. Varve counting errors were estimated in intervals of 100 years. Three repeated varve counts by the same analyst were compared (Lotter and Lemcke 1999). The cumulative counting error was estimated to be between –2.5% (56 varve years) and +2.3% (53 varve years) (Fig. 6). Maximum deviations were -5.6% and +5.9%, observed from BP 950-850 and BP 450-350, respectively. Counting errors result from indistinct varve boundaries, which are perhaps artefacts related to coring and subsampling. But it is possible that these varves are just poorly preserved. The interval with the highest varve quality (BP 1650-1550) had the lowest count error (0%). Our error estimates are in line with other varve chronologies (Snowball et al. 1999; Tiljander et al. 2003; Haltia-Hovi et al. 2007). Varve counting errors may result in differences between varve years and calendar years. This can lead to offsets in timing between observed and reconstructed data, which in turn alters correlation coefficient values between observed data and their putative proxy variables.

Discussion

Varve thickness versus meteorological data

The TOT and GSL data were compared with recent meteorological data to identify the climate variables that affect sedimentation. Several periods display high, statistically significant correlation values (Table 3). Generally, TOT correlates positively with P_{ann}, and GSL correlates positively with P_{gs} (Table 3). Greater varve thickness occurs during years with high precipitation, whereas varve thickness is smaller during drier periods (Fig. 7).

About 40% of total annual precipitation in Central Finland falls as snow. Snow accumulation has an important role in boreal lake systems, because it controls the amount of water released during the spring melt. Flooding enhances catchment erosion and transport of allochthonous organic matter and nutrients into a lake. This may explain the more frequent episodes of correlation between P_{ann} and TOT than of P_{gs} and GSL (Table 3).

Rainfall during the growing season increases the transfer of organic matter and nutrients from the catchment to the lake (De Stasio et al. 1996). The C/N values of 19-22 in the sediment record suggest dominance of organic material from terrestrial origin (Meyers and Ishiwatari 1993) and support the importance of precipitation as a transport medium. Several studies have reported increased accumulation rates of organic matter as a consequence of greater precipitation (Itkonen and Salonen 1994; Tian et al. 2011).

Periods of negative correlation between GSL and T_{gs} (1913-1922 and 1947-1957), and an episode of pronounced positive correlation (1963-1980) suggest a more complex relationship between GSL thickness and temperature (Fig. 7). Gudasz et al. (2010) reported more efficient organic carbon (OC) mineralization in lake sediments with increased water temperatures, and Haltia-Hovi et al. (2007) found that the thinnest organic laminae from Lake Lehmilampi accumulated during warmer medieval times. In small lakes like Lehmilampi and Kallio-Kourujärvi, surface waters may warm to more than 25°C during summer months. This could increase OC mineralization and enhance degradation of organic matter in the water column, both of which would decrease the amount of organic matter that accumulates in sediments. Microbial reworking of organic matter during sedimentation through the water column considerably diminishes the total amount of organic matter that accumulates (Meyers and Lallier-Vergès 1999).

Temperature controls the length of the growing season and duration of spring and fall overturns, which result in nutrient upwelling from the hypolimnion to the epilimnion. Elevated temperatures in spring, summer, and autumn lead to stronger and more prolonged stratification (Jankowski et al. 2006; Sobek et al. 2009). The timing and stability of thermal stratification could affect GSL thickness by restricting the nutrient availability, leading to the cessation of diatom blooms (Bradbury 1988; De Stasio et al. 1996). Diatoms are frequent in GSL and a decrease in diatom abundance may partly explain thinner GSL. However, the response of algal populations to warming is dependent on the nutrient availability (DeStasio et al. 1996) and in this regard, both precipitation and the length and intensity of the overturns are important. This may partly explain the nonlinear correlation between GSL and T_{gr}.

There is no evidence for major changes in temperature or precipitation that would explain the simultaneous reversal of correlations between varve thickness and climate variables (Table 3, Fig. 7). Only comparisons of several records would enable evaluation of whether climate variables such as storm events, length of ice-free periods, snow accumulation or perhaps human activities caused the inverse correlation during the period AD 1960-1980.

WL thickness shows low variability, but increased WL thickness, which coincides with enhanced GSL thickness, presumably because after a highly productive summer there is more fine-grained organic material in the water column that settles under the ice. The length of the ice-free period and wind-induced sediment resuspension could, however, affect WL thickness. Even a single storm event may re-suspend littoral sediments, which can be transported to the profundal zone (Bengtsson et al. 1990). Warm winters shorten the time of ice cover and expose littoral sediments to wind and wave reworking, thereby favoring accumulation of thicker varves (Itkonen and Salonen 1994).

The lake response to the climate signal may not be linear and the intensity of climate forcing may vary considerably, leading to poor correlation between climate variables and varve thickness. Furthermore, lake sediment variables are affected by multiple climatic and non-climatic factors, and thus it is difficult to infer the cause of observed changes in lake deposits (Tian et al. 2011). In addition, local thunderstorms may influence the correlation coefficients.

Inferring past climate from varve data should be done with caution, bearing in mind all the factors, in addition to climate variables, that affect catchment dynamics and the accumulating lacustrine sediments. However, our analyses indicate a general increase in varve thickness during periods of higher precipitation. Thinner varves occur with lower precipitation as a consequence of reduced catchment erosion and nutrient limitation. Temperature may influence varve thickness, too, but the effect is nonlinear and unpredictable. Prolonged direct lake stratification may result in reduced nutrient input and stronger degradation of organic matter, thereby favoring formation of thin varves.

Paleoenvironmental and paleoclimate changes in Central Finland

Large inter-annual differences in varve thickness recorded in this study suggest a wide range of climate variations during the last 3,000 years. This time period extends beyond the climate intervals of the Little Ice Age (Grove 2001; Miller et al. 2010) and the Medieval Climate Anomaly (Hughes and Diaz 1994; Miller et al. 2010), to include the transition from the Sub-Boreal to the Sub-Atlantic (Wanner et al. 2008).

Large-scale precipitation trends inferred from Lake Kallio-Kourujärvi sediments contain periods of both mesic and dry conditions (Fig. 8) that are in line with reconstructed lake level changes from Central Finland (Luoto 2009), peat humification fluctuations from Central Sweden (Gunnarson et al. 2003) and effective precipitation in West Scandinavia (De Jong et al. 2009). This suggests that ocean and atmosphere processes are important influences on large-scale climate trends in Central Finland. The relatively dry climate shifted to more variable and humid conditions around 2,500 BP, following the general late Holocene climate evolution of the Northern Hemisphere from the Sub-Boreal to the more humid Sub-Atlantic (Miller et al. 2010; Wanner et al. 2008).

There are decadal periods of increased TOT and GSL thickness, implying enhanced precipitation during BP 2150-2090, 1710-1620, 1410-1360, 920-870, and after 370 BP (1580 AD) until the present day (Fig. 8), the most recent reflecting the onset of the Little Ice Age (LIA). Enhanced organic matter accumulation in Kallio-Kourujärvi during the LIA is in agreement with increased organic lamina thickness observed in Finnish clastic-organic varve records (Tiljander et al. 2003; Haltia-Hovi et al. 2007).

Low TOT and GSL thickness occurs at BP 2750-2720, 1900-1850, 1800-1740, 1600-1500, and 780-700 (1170-1250 AD), 590-520 (1360-1430 AD). These are interpreted as periods of decreased precipitation, and the two most recent episodes correspond to the Medieval Climate Anomaly (MCA). Several of these intervals coincide with lower organic matter accumulation in Lakes Korttajärvi (Tiljander et al. 2003), Nautajärvi (Ojala and Alenius 2005) and Lehmilampi (Haltia-Hovi et al. 2007), which suggest widespread decreased precipitation in Central and Eastern Finland. Synchronous droughts are also observed from other parts of Scandinavia (De Jong et al. 2009; Gunnarson et al. 2003).

The low and very constant level of TOT and GSL between 780 and 700 BP (1170-1250 AD) represents a period of low climate variability and decreased annual precipitation, as suggested earlier by Helama et al. (2009). Low organic matter accumulation and low variability is observed in Lake Korttajärvi during this period, as well (Tiljander et. al., 2003). Highest variability in the Lake Kallio-Kourujärvi record is observed during 1720-850 BP and since 370 BP (1580 AD) until present, suggesting large inter-annual variations in precipitation. These unstable periods are consistent with the climate reconstructions of Helama et al. (2009), linked to the El Niño Southern Oscillation – North Atlantic Oscillation (ENSO – NAO) variability. Although it is likely that large-scale climate patterns affect organic varve formation, the Lake Kallio-Kourujärvi record does not reflect details of either reconstructed NAO or ENSO variation. This is perhaps explained by the nature of the Kallio-Kourujärvi sediment, which is strongly influenced by growing season conditions, whereas ENSO and NAO appear strongest during winter.

There are very few reconstructions of paleo-precipitation from Central Finland. The record from Lake Kallio-Kourujärvi agrees, in general, with previous reconstructions from

Southern and Central Finland (Väliranta et al. 2007; Helama and Lindholm 2003; Luoto 2009) and other parts of Scandinavia (De Jong et al. 2009; Gunnarson et al. 2003). This suggests that organic varve thickness may serve as a reliable proxy for paleo-precipitation, with the advantage that such varve records are much longer than tree-ring records and provide higher temporal resolution compared to radiocarbon-dated lake sequences.

Recent sedimentation and human influence

The increasing trend in thickness of TOT, GSL, and WL since AD 1600 may reflect intensified human land use activities such as slash-and-burn cultivation. Varve thickness peaks at 1890, reflecting modern land use changes around the lake, such as logging, ditching and infrastructure construction such as road building (Fig. 1), all of which lead to decreased vegetation cover and increased erosion. Furthermore, minerogenic laminae (ML) occur increasingly between WL and GSL since AD 1890, and result from watershed erosion during spring floods. Increased varve thicknesses are generally observed in Finnish varve records in the 20th century and are related to increased human land use (Itkonen and Salonen 1994; Tiljander et al. 2003; Meriläinen et al. 2010)

Conclusions

This study presents a unique organic varve sediment record from Lake Kallio-Kourujärvi, Central Finland. The high-quality varve record yielded a counting error between -2.5% (missing varves) and +2.3% (surplus varves) and covers 3,000 varve years.

Positive correlation between organic varve thickness and annual precipitation suggests that precipitation plays an important role in organic varve formation in Lake Kallio-

Kourujärvi. Greater precipitation enhances organic matter and nutrient transport from the catchment, which favors increased varve thickness. Thus, organic varves show great potential as a proxy for paleo-precipitation.

The correlation between temperature and growing-season lamina thickness varied from absent, to positive, to negative during different time spans. This suggests that organic matter accumulation can sometimes have a significant, but unpredictable role in organic varve formation.

Our results suggest that decadal periods of higher precipitation occurred during BP 2150-2090, 1710-1620, 1410-1360, 920-870 (1030-1080 AD), and after 370 BP (1580 AD). Dryer intervals occurred during BP 2750-2720, 1900-1850, 1800-1740, 1600-1500, and 780-700 (1170-1250 AD), 590-520 (1360-1430 AD).

The large inter-annual variability during 1400-880 BP and from 370 BP occurred during enhanced variability of the NAO. Very low variability of varve thickness during the interval 850-700 BP coincided with low NAO variability. This suggests that the North Atlantic Oscillation plays a large role in climate stability in Central Finland.

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Figure Legends

Fig. 1 Bathymetric map of Lake Kallio-Kourujärvi, showing the coring site (cross) in the deepest basin and characteristics of the catchment area. Insert shows the location of Lake Kallio-Kourujärvi (cross), Jyväskylä meteorological station (square) in Scandinavia and the location of the lakes (1-3) that are used as references for paleomagnetic dating

Fig. 2 (**A**) Microscopic image of the sediment at a depth of 28 cm, under dark-field illumination. Bright laminae represent growing-season sedimentation between spring and autumn overturns, whereas thin, dark laminae are formed during winter ice periods. (**B**) Schematic figure illustrating the composition of a varve. (**C**) Climate diagram showing monthly average precipitation and air temperature for the period 1960-1990. Data are from the Jyväskylä meteorological station (NORDKLIM), 75 km southwest of the study site. The blocks under the diagram mark the times within the year of lamina formation

Fig. 3 Studied variables total varve thickness (TOT), growing season lamina (GSL) thickness, and winter lamina (WL) thickness. The grey line shows raw data and the black line displays the 21-year moving average. A line parallel to the x-axis demonstrates the median thickness of the varve variable for the entire chronology

Fig. 4 Low-field magnetic susceptibility (κ_{LF}) of cores KKJ-2 and KKJ-3.

Fig. 5 Paleo Secular Variation (PSV) from Lake Kallio-Kourujärvi compared to varve-dated PSV records from Lakes Lehmilampi, Kortejärvi, and Nautajärvi. (**A**) Inclination (**B**) relative declination

Fig. 6 Cumulative varve counting error estimates

Fig. 7 Varve data compared with meteorological data for the last 110 years, all shown as 5-year moving averages (**A**) Growing season lamina thickness variation (GSL: black line) and growing season temperature (T_{gs}: dash line). (**B**) Total varve thickness variation (TOT: black line) and annual precipitation (P_{ann}: dash line) from the Jyväskylä meteorological station. Periods of highest positive and negative correlation are highlighted

Fig. 8 Smoothed varve thickness record (TOT: 51-year running average) showing inferred precipitation trends over the past 3,000 years. The increased precipitation after 2,500 BP is related to the shift from the Sub-Boreal to Sub-Atlantic.

Table 1 Abbreviations and their definitions

Abbreviation	Definition
GSL	Growing season (April-September) lamina
WL	Winter lamina
ML	Minerogenic lamina
TOT	Total varve
P_{ann}	Annual precipitation
P_{gs}	Precipitation of the growing season
T_{gs}	Temperature mean of the growing season

Table 2 Summary of the varve physical properties

	TOT (mm)	GSL (mm)	WL (mm)
Minimum thickness	0.1	0.05	0.01
Maximum thickness	1.9	1.7	0.8
Mean thickness	0.46	0.35	0.11
Median thickness	0.4	0.3	0.1

Table 3 Intervals with the highest correlation coefficients

Period (AD)	Variables		r	*p* value
1906–1920	Pgs	TOT	0.55	0.028
1906–1922	Pann	TOT	0.55	0.028
1913–1922	Tgs	GSL	–0.74	0.015
1928–1944	Pann	TOT	0.60	0.011
1947–1957	Tgs	GSL	–0.69	0.019
1947–1959	Pann	TOT	0.64	0.017
1959–1974	Pann	TOT	–0.55	0.026
1963–1980	Tgs	GSL	0.50	0.034
1966–1975	Pgs	GSL	–0.70	0.020
1986–1996	Pgs	GSL	0.64	0.033
1986–1996	Pann	TOT	0.69	0.018