Winter climate signal in boreal clastic-biogenic varves: a comprehensive analysis of three varved records from 1890 to 1990 AD with meteorological and hydrological data from eastern Finland

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Abstract

Clastic-biogenic varves are widely used for reconstructing past climate: in boreal environments, the accumulation of minerogenic clasts on the lake floor is generally considered a proxy for past variations in spring floods reflecting previous winter conditions. However, the physical mechanisms behind this winter climate sensitivity and the influence of catchment type on the varve formation are not fully investigated. Here, we present a winter climate record inferred from the clastic laminae of three lakes located on the region of fine-grained tills in eastern Finland spanning from AD 1890 to 1990. The minerogenic varve data is compared with instrumental meteorological and hydrological time series in order to investigate the physical link between winter and spring climate and minerogenic matter accumulation. Our analyses reveal that the climate-catchment mechanisms operating in the region of fine-grained tills in eastern Finland differ crucially from previously described climate catchment interactions on sand moraine-dominated catchments in central Finland. Usually the maximum river discharge in spring controls the clastic lamina formation. However, in contrast to earlier boreal varve records from central Finland, the clastic lamina formation in the studied region correlates negatively with spring temperatures and winter precipitation. This could be an artefact of varying catchment dynamics but also related to the regional climate. The lakes surrounded by catchments characterized by fine-grained tills are more sensitive to cold and dry winters. The differences in the sensitivity of varve characteristics to climate, highlights the importance of understanding the catchment dynamics in detail in order to better understand climatic forcing.

Keywords: clastic-biogenic varves, lake sediments, boreal climate, Northern Europe, catchment dynamics, fine-grained tills, climate forcing

Introduction

Annually laminated (varved) sediments are widely used for reconstructing past climatic changes (Brauer et al., 2009; Ojala et al., 2012; Zolitschka et al., 2015). The advantages of using varved sediments in paleoclimatological and environmental studies include accurate and precise temporal control, which enables studies even on sub-annual scales (Dean et al., 1999; Tiljander et al., 2002), and the potential to reconstruct continuous varve time series, which may reach back in time over tens of thousands of years (Vos et al., 1997; Ojala and Alenius, 2005; Kitagawa and Plicht, 2006;). These features provide a unique possibility to observe past changes over long time intervals in exceptionally high resolution.

Lake environments are sensitive to environmental and climate conditions due to restricted catchment areas, limited water exchange in the basin, and small water volume (Renberg, 1981; Tiljander, 2003; Zolitschka et al., 2015). However, each lake responds uniquely to climatic forcing. Ultimately, catchment composition, topography, and morphology control the availability of minerogenic particles and nutrients (Ojala et al., 2012). Varve characteristics are influenced not only by direct climate variations but also indirectly through, for example, forest fires and changes in catchment vegetation. These factors can greatly affect sedimentation as well as the non-climatic factors that include natural shallowing of the lakes by sediment filling and human actions. Such factors lead to challenges in extracting the environmental and anthropogenic influence from climatic forcing.

Dendrochronological studies favor sampling multiple trees in a study area to smooth out random events, which may affect individual trees. However, it is relatively rare to compare multiple varve records from the same study area. This is due to the high costs of sampling, the scattered occurrence of the lakes with annually laminated sediments, in addition to the time-consuming sample preparation and varve counting. Therefore, few studies from multiple varved lake records exist (Desloges, 1994; Itkonen and Salonen, 1994; Snowball et al., 2002; Gälman et al., 2006). The exceptionally dense occurrence of lakes – and varved lakes – in Finland enables the study of several varve records in a reasonably small area. This provides a unique possibility to evaluate the importance of regional climate and catchment processes to the recorded changes in varves.

The future changes in the boreal climate are expected to be larger and more pronounced during winters (IPCC 2013). Thus, understanding the winter climate variability in the past is crucial to evaluating future changes. To estimate the importance of winter climate and climatic variables, such as winter precipitation, temperature, and snow accumulation, to varve characteristics, a comparison of recent varve characteristics with climatic variables from instrumental weather records is greatly needed. Several studies, which compare detailed instrumental and varve data, already exist (Leemann and Niessen, 1994; Ohlendorf et al., 1997; Wohlfarth et al., 1998; Larocque et al., 2009; Tian et al., 2011). However, climatic variables have varying importance on varve characteristics in different depositional environments. There are only a few studies concerning the influence of climatic variables on varve characteristics in boreal zones (Itkonen and Salonen, 1994; Gälman et al., 2006; Ojala et al., 2013; 2014) and even fewer evaluating the winter climate response in several boreal lakes. However, it has been observed that total varve thickness variation is not the only meaningful way to study past climate variation since organic and clastic compounds are largely influenced by different mechanisms (Ojala et al., 2013).

It may be misleading to generalize the relationship between climatic variables and varve characteristics based on a single lake. Each lake and its catchment dynamics should be studied in detail, such as size, upper water systems, diversity of soil formations, and topography that influence the availability, erosion, and transport of clastic materials.

Several previous boreal and arctic varve studies have suggested that enhanced minerogenic clast accumulation is related to increased snow accumulation (Francus et al., 2002; Tiljander et al., 2003; Ojala et al., 2013; 2015; Zolitschka et al., 2015; Saarni et al., 2016a). However, a recent study of Lake Kuninkaisenlampi in eastern Finland suggests increased clastic lamina thicknesses as a result of decreased snow accumulation (Saarni et al., 2016b). The catchment of Lake Kuninkaisenlampi is located in a special region characterized by fine-grained tills. This region in Finland, where the tills are rich in fine fractions, extends from the northern part of the west-coast towards the southeast all the way to eastern Finland (Figure 1; Lintinen, 1995; Punkari, 1997) and is formed on the interlobate areas of the Scandinavian ice sheet (Punkari, 1997; Lunkka et al., 2004). In general, fine grained tills are found sporadically at the areas covered by Laurentide and Eurasian ice sheets e.g. from Scandinavia (Punkari, 1997; Lindh and Winter, 2003) and North America (Clark and Walder 1994; Viklander, 1998). Till is classified as being rich in fines if it contains more than 5% of clay fractions and more than 30% of silt fractions (Lindroos and Nieminen 1982, Lintinen, 1995). The fine-grained tills are very sensitive to frost development (Viklander, 1998; Haavisto-Hyvärinen and Kutvonen, 2007). Furthermore, fine-grained tills are rich in nutrients leading to the naturally high trophic states of the lakes (Kukkonen and Sahala 1988; Kauppila et al., 2012; Tammelin and Kauppila, 2015; Tammelin et al., 2017). Varve formation in lakes on the catchments rich in fine-grained tills have never been studied in detail.

We compared winter climate variables from instrumental meteorological and hydrological data with varve characteristics from three small boreal lakes located in the area of fine-grained tills. This was carried out in order to better understand the mechanisms mediating the winter climate signal to the varve characteristics on this special catchment type. The objective of this study was to assess the importance of winter climatic variables including: temperature, precipitation, snow accumulation, ice cover duration, river discharge, and boreal spring conditions responsible for the characteristics of the clastic lamina. We used varve records from three lakes to investigate the role of fine-grained tills in the different responses of varve formation to climate forcing and to observe how well the correlations of the variables can be generalized between the small lakes with catchments of fine-grained tills.

Material and methods

Site descriptions

The study area of 1350 km^2, located in eastern Finland, extends 65 km in a north-south direction and 75 km in an east-west direction. Three dimictic lakes with very similar catchments were chosen for this study (Figure 1): Linnanlampi, LIN, Kantele, KNT and Kuninkaisenlampi, KUN (Saarni et al., 2016b). The lake basins were formed after the deglaciation of the Weichselian ice sheet. Immediately after the ice sheet retreat, the lakes were submerged by the early Baltic Sea stage, the Ancylus Lake, from which the lakes were isolated one by one after 9 500 years BP (Saarnisto, 2000). After the Ancylus stage, the region was partly covered by the large water body of the ancient Lake Suursaimaa, from which Lake Linnanlampi was isolated around 6000 BP (Saarnisto, 2000). The timing of the isolation of Lake Kantele and Kuninkaisenlampi is not exactly known, but it is very likely related to isostatic uplift and bifurcation of the ancient Lake Suursaimaa at around 6000 BP (Hakulinen 2009). The catchments of the lakes are generally composed of fine-grained Quaternary tills (Lintinen, 1995; Maankamara - DigiKP), where the clay fraction can be up to 30% (Lintinen, 1995). Minor formations of Carex and Sphagnum peat and some bedrock outcrops occur in the catchments (Figure 1; Table 1; Maankamara - DigiKP). At present, the study area is situated in the boreal vegetation zone dominated by coniferous forests (Ruuhijärvi, 1988) and characterized by snowy winters and mild summers.

The common features of the lakes include a small surface area, a small area at the deepest part of the basin, and maximum water depths of between 10.0 and 12.0 m (Table 1). At present, there is cultivation and forest industry in the catchments of each lake, but only minor human residency.

Coring

The coring was carried out through the ice cover during the winters of 2008 and 2009. The deepest part of each lake was cored using a rod-operated piston corer (Figure 1). Undisturbed surface samples were obtained using a mini-ice finger technique (Renberg, 1981; Saarinen and Wenho, 2005), where a 35 cm long wedge-shaped hollow aluminum tube was pushed slowly into the surface sediments obtained using a cable-operated Limnos gravity corer (Kansanen et al., 1991). The aluminum tube was filled with dry ice and the topmost sediments, including the water-sediment interface, were frozen around the mini ice finger. Several parallel freeze cores were taken from each lake.

Sample preparation and impregnation in epoxy

Sediment cores were carefully opened in the laboratory with a circular saw and a wire. Sub-sampling of the measurement of varve parameters was carried out in the manner described in Haltia-Hovi *et al.* (2007). The sediment sequences were sub-sampled continuously using 11 cm long aluminum molds with a 1.5 cm overlap for sediment embedding.

Sub-samples were impregnated in a modified 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 (Moran et al., 1989; Haltia-Hovi et al., 2007). The epoxy was changed six times, however, in the first two epoxy batches a small amount of acetone was added in order to improve impregnation (Pike and Kemp, 1996). Samples were cured at 60°C for 48 h. Each sub-sample block was polished carefully using a grinding machine and thin sections with a thickness of 130 μm were made in the Section of Geology at the University of Turku.

Varve counting

Freeze core samples were used to link the chronologies to the present. Freeze cores were levelled with a plane and the varves were counted from the cleaned surface with a stereographic microscope. The freeze core samples were visually correlated with the epoxy impregnated sediment sub-samples using several marker layers. The chronologies were constructed from polished subsamples and thin sections using a stereographic microscope (Nikon SMZ800) with a 6x magnification. The varve boundaries were determined and clastic lamina thickness (CL) was measured using an ocular scale. Varve chronologies were constructed based on three counts and error margins were evaluated based on the deviation between the counts from each lake (Lotter and Lemcke, 1999).

Climate and hydrological data

Climate data was downloaded from the NORDKLIM database (NORDMET steering committee, 2002). Kuopio meteorological station was chosen because of its proximity with respect to the lakes studied and the temporal duration and continuity of the climate data time series. The distance between the lakes studied and the meteorological station is less than 85 km (Figure 1, Table 2). There were no meteorological stations in the lake catchments and the time series from the nearest meteorological stations were fragmented and exhibited very limited temporal extent. The climate variables include air temperature, precipitation, the duration of ice cover, precipitation sum, and the temperature of May, as well as the precipitation sum of the winter months (November-April), which is calculated from the monthly data.

The hydrological data was downloaded from the HERTTA database administrated by the Finnish Environment Institute (http://www.syke.fi/fi-FI/Avoin_tieto/Ymparistotieto jarjestelmat). The variables included daily river discharge data (m^3/s), snow pack water equivalent data (mm), and the dates of development and melting of ice cover. River discharge data was gathered from the nearest available location in the vicinity of each lake (Table 2). River discharge data was evaluated for each lake separately (Table 2). The maximum discharge (Q_{max}) was observed from the daily data and the mean discharge of the spring months (Q_{amj}; from April to June) was calculated for each year. The duration of ice cover (ICE), expressed as number of days with ice cover, was calculated from freezing and thawing dates. Snow pack water equivalent data (SWE) was downloaded from the HERTTA database as well. The early April values, which generally exhibited the annual SWE maxima, were used for this study as they reflected the snow conditions at the initiation of the melting seasons.

Statistical analysis

Principal component analysis (PCA) for the three lakes was run with PAST 3.14 software (Hammer et al., 2001) in order to reduce the dimensionality of the multivariate data, find underlying structures, and estimate the importance of and relationships between the varve, climatic, and hydrological variables. As the variables had different units, a correlation matrix was used. Missing data in the hydrological data as well as in the duration of ice cover and snow water equivalent data were treated with iterative imputation. For correlation analysis, the R 2.14.1 program (R Development Core Team, 2011) was used in order to study correlations between the variables: winter precipitation, the duration of ice cover, the snow water equivalent, maximum river discharge, mean spring river discharge, spring temperature, winter temperature and total clastic lamina thicknesses from each lake for the 100-year interval. Pearson's correlation analyses were performed and the Shapiro Wilk test was used to verify the normal distribution of the samples. When this was not the case, Spearman's rank correlation coefficient based correlation analysis was used instead. An 11-year moving average of varve parameters and climatic data was used for the long time series (winter precipitation) to smooth out any inaccuracy in varve dating (Itkonen and Salonen, 1994). No smoothing was used for the hydrological data because of the short temporal extent of the data (Table 2).

Results

Sediment descriptions

The sediments of each lake are continuously varved from the present to well beyond the last 120 years. The varves are of a clastic-biogenic varve type (O'Sullivan, 1983; Haltia-Hovi et al., 2007; Ojala et al., 2013), where each varve consists of a clastic and a biogenic component (Figure 2). A varve year begins in spring, when the melting snow causes flooding and increased erosion on the lake watershed. Eroded clastic particles settle down onto the lake floor to produce a lamina composed of minerogenic clasts, mainly consisting of quartz and feldspar, which are the most common constituents of the plutonic rocks dominating the bedrock in the study region. The second lamina, which lies on top of the minerogenic clastic lamina, consists of organic material of autochthonous and allochthonous origin, produced during growing season, and of the finest, highly degraded amorphous organic particles that settle down onto the lake floor under the ice cover. The topmost varves of each lake are considerably thicker due to high water content and low compaction of the surface sediments. For this reason, the topmost laminae are excluded from the data and used only for constructing the varve chronology from each lake. The studied time interval is thus from 1890 to 1990 AD.

Varve parameters

This study is focused on winter climate forcing on sedimentation and, thus, only the variation of clastic laminae thicknesses (CL), dependent on winter and spring conditions, are studied. CL was observed using microscopic analysis yielding a lamina thickness variation in mm. In each lake, the varve boundaries were easy to determine because the contact between organic and minerogenic matter is sharp due to the short but high intensity spring flood event and the consequent rapid sedimentation of the minerogenic particles. The clastic lamina thickness varies from less than 0.1 mm to nearly 1.0 mm (Table 3).

All three sediment records show clear fluctuations in the clastic matter accumulation (Figure 3). The minerogenic matter accumulation increased significantly in AD 1906 in Lake Linnanlampi and in AD 1917 in Lake Kuninkaisenlampi, and shows a large amplitude and enhanced erosion for about 20 years. The sediment record of Lake Kantele shows sudden increases of minerogenic clast accumulation in AD 1893, 1929 and 1954, although these periods only last for approximately five years. The correlation between Lake Linnanlampi and Lake Kuninkaisenlampi CL is positive ($r = 0.57$) while the correlation between Lake Kantele and Kuninkaisenlampi and Lake Kantele and Linnanlampi were less significant ($r = 0.2$ and $r = -0.27$, respectively).

Varve chronology and error estimation

The error estimate of the varve chronology from a previously studied 3600-year record from Kuninkaisenlampi (Saarni et al. 2016b) is reported to be 2.6%, however, for the topmost hundred years (AD 1890-1990) an error estimate of only 0.7% is reported (Table 3). The error estimations from Lake Linnanlampi and Kantele were evaluated following the method described by Lotter and Lemcke (1999). The 110-year long varve intervals were calculated three times and performed from a different analytical line each time. The error estimates, calculated as deviation from the mean of the three counts, were 0.3 % for Lake Kantele and 1.0 % for Lake Linnanlampi. The very low error estimate for Lake Kantele is explained by the very clear and well preserved varve structure. The error margin of Lake Linnanlampi is in line with the uncertainty range associated with lake varve chronologies in general (Ojala et al., 2012; Zolitschka et al., 2015). However, the temporal extent of the records in question is only 100 years. The very low error margin of Lake Kantele is in line with varve chronologies in general: the 100-year periods with a counting deviation of 0 % are reported in several longer clastic-biogenic varve chronologies (Haltia-Hovi et al., 2007; Saarni et al., 2016a; Saarni et al., 2016b).

Climatic variability

The annual mean temperature in Kuopio (62°54’N 27°41’E) is 3.0°C (AD 1961-1990). The coldest month is January (-10.3°C) and the warmest July (16.6°C). The cumulative precipitation of winter months (November-April) varies between 136 and 396 mm (mean 246 mm) and snow pack in water equivalent values varies from 69-216 mm (Lake Kantele) to 85-262 (Lake Kuninkaisenlampi). The duration of ice cover varies between 127-210 days, being generally longest at the Lake Kantele location. Each stream is unique due to differences in catchment topography and soil type, which is why the numerical discharge data cannot be directly compared between the monitored streams. However, the most intensive river discharge was usually measured in May at each study site. The duration of the spring flood (Qdur) is defined to cover the period when the discharge exceeds the calculated mean discharge of the melting season (April-June) (Saarni et al., 2016b). The length of the flood event varies greatly from year to year, from a few days to more than two months. The variation in flood event duration is smallest at Lake Linnanlampi (17-69 days) and highest at Lake Kuninkaisenlampi (5-73 days).

Statistical results

According to the PCA ordination biplot (Figure 4), the first and second principal components explained most of the variance in the data, 38.16% and 21.26%, respectively. The biplot shows, for example, that clastic laminae are thicker and the duration of ice cover longer when the spring and winter temperatures and winter precipitation are lower. Similarly, the clastic laminae are thicker when river discharge and spring precipitation are high.

Correlations were studied in detail between clastic minerogenic laminae thickness and climatic variables. Where possible, the longest statistically significant periods ($p < 0.05$) and the periods with the highest statistically significant correlations ($p < 0.05$) were investigated. In addition, correlations approaching the statistical significance level ($p \leq 0.1$) were considered. Generally, positive correlations were observed between the maximum river discharge and the minerogenic matter accumulation at Lakes Linnanlampi and Kuninkaisenlampi, but a negative correlation was observed for Lake Kantele. The correlation between minerogenic matter accumulation and spring temperature were either negative or positive, but for snow accumulation and winter precipitation consistently negative (Table 4).

Discussion

The PCA suggests that prolonged ice cover periods are coeval with cold winter and May temperatures. Mean winter temperature in the study area falls substantially below zero every year leading to the development of continuous ice cover from 120 to 210 days (Table 2; Figure 5). Therefore, the winter temperature is not the most effective factor to explain ice cover duration, but instead it is dependent on autumn and spring temperatures. The May temperature regulates the length of the ice cover period and the timing and duration of the flood episode (Figure 4, Figure 5). At each study site, the flood episode occurred between April and June and lasted less than 91 days indicating that these months are representative when studying spring floods. Only 5% of flood peaks occurred in April and 5% in June during the monitored period at River Koivujoki near Lake Kantele. At River Viannonkoski (Lakes Linnanlampi) and River Karjalankoski (Lake Kuninkaisenlampi) none of the flood peaks occurred in April, but 18% and 10% occurred in June, respectively. This suggests that the mean May temperature is a predictive factor for evaluating the importance of a flood episode

(Figure 4), and for studying the influence of spring climate conditions on clastic lamina characteristics.

The maximum river discharge correlates positively with the accumulation of minerogenic matter at Lake Kuninkaisenlampi and Lake Linnanlampi (Table 4), which is in line with the earlier interpretations of the importance of spring flooding as a transport mechanism of clastic particles (Renberg, 1981; O'Sullivan, 1983) and is supported by the PCA biplot (Figure 4). Recently, the link between clast accumulation and spring river discharge in a boreal environment was studied in detail (Ojala et al., 2013; 2014). The minerogenic particles are washed into the lake basin from the catchment during the spring floods. Higher discharge events were observed to transport larger minerogenic particles (Francus et al., 2002; Sander et al., 2002; Ojala et al., 2013). However, negative correlations were found between clastic matter accumulation in Lake Kantele and maximum discharge and mean flood period discharge. This relationship could possibly be an artefact of the River Koivujoki where the discharge is very low throughout the year and the catchment is composed largely of peat lands (Luukkanen 1983; HERTTA; Maankamara–DigiKP) unlike the fine-grained till soils of Lake Kantele's catchment with only fragmented and small peat covered areas. Negative correlations and earlier flood peaks in River Koivujoki compared to the other study sites could be explained by runoff generation in boreal peat soils. The snow melt water in peat lands has been observed to run off as overland flow, especially at the onset of the snow melt episode, when the frost inhibits melt water infiltration (Laudon et al., 2007; Eskelinen et al., 2016). As melting proceeds, the capacity of peat formation to absorb the snow melt waters quickly increases (Laudon et al., 2007; Eskelinen et al., 2016). This mechanism could advance the observed flood peak and flatten the flood episode which is actually observed in River Koivujoki (HERTTA). Due to the large peat areas in the River Koivujoki catchment, the river discharge cannot be expected to reflect the river discharge in the adjacent catchment of Lake Kantele, which is dominated by mineral soils.

Catchment dynamics

Spring flood intensity described as maximum river discharge are considered to be a function of enhanced snow accumulation (Renberg, 1981; Francus et al., 2002; Sander et al., 2002; Ojala et al., 2013) which also seems to be the case in the three studied lakes according to the PCA biplotl (Figure 4). Earlier studies of Lakes Korttajärvi (Tiljander et al., 2003; Ojala et al., 2015) and Kalliojärvi (Saarni et al., 2016a) from central Finland suggest that clastic accumulation is related to snow accumulation. The positive correlations between the Lake Korttajärvi and Kalliojärvi proxies reflect the fact that clastic accumulation and winter precipitation are related (r = 0.59, r = 0.61, respectively, unpublished results) as well as clastic accumulation and winter temperature (r = 0.39, r = 0.34) and spring temperature (r = 0.26, r = 0.39). According to PCA biplot the clastic matter accumulation in the three studied lakes is higher when river discharge is enhanced implying that river discharge is important for the clastic matter accumulation. However our results also suggests that the interactions between clast accumulation and winter precipitation or spring temperature, are not as straightforward in the case of these three study lakes compared to previously investigated Lake Korttajärvi and Kalliojärvi sites. The more detailed investigation of correlations suggests that clastic accumulation is interestingly enhanced as a result of dryer winters and colder springs (Table 4, Figure 6). The cold springs, reflected as prolonged ice cover duration in addition to low May mean temperature, are related to increased minerogenic clast transport and accumulation in Lakes Linnanlampi and Kuninkaisenlampi (Table 4, Figure 4, Figure 6). This contradicts the previous studies from Korttajärvi (Tiljander et al., 2003) and Kalliojärvi (Saarni et al., 2016a), as both showed enhanced minerogenic accumulation during mild springs.

The discrepancy between our study and the previous studies could be explained either by the differences in the catchment areas or in the regional climate. Lakes Korttajärvi and Kalliojärvi are located on catchments dominated by sandy tills and minerogenic matter accumulation is controlled by snow accumulation. Fine-grained soils and especially fine-grained tills, on the other hand, are very sensitive to frost, whereas sand tills are not. Snow isolates very well and a weak snow cover is related to deeper soil frost formation (Stadler et al., 1996; Hardy et al., 2001). We suggest that catchments rich in fine-grained tills, in general, experience more permanent frost related to cold spring temperature. During the melting season, a lower infiltration rate of melt water into the frozen soil increases surface runoff and enhances surface erosion (Hardy et al., 2001; Johansson and Lundin, 1991; Ojala et al., 2013; 2014). Furthermore, decreased winter precipitation has been shown to prolong frost duration and frost depth significantly (Stadler et al., 1996; Granberg et al., 1999; Hardy et al., 2001; Lindström et al., 2002). Therefore, lake catchments dominated by fine-grained tills appear to be more sensitive to frost than to enhanced snow accumulation.

Regional climate

The increased clast accumulation appears to be related to both cold spring temperatures and decreased winter precipitation (Figure 4, Figure 6) although in Lake Kantele this is not as clear. However, such relationships contradict earlier suggestions of winter climatic forcing mechanisms revealed by clastic-biogenic varve records from central Finland.

Both previously studied Lakes Korttajärvi (Tiljander et al., 2003) and Kalliojärvi (Saarni et al., 2016a) are at a more westerly location in Finland with a stronger marine influence. The minerogenic matter accumulation at these two lakes have earlier been related to the North Atlantic Oscillation (NAO; Tiljander et al., 2003; Ojala et al., 2015; Saarni et al., 2016a). The 3000-year long record from Korttajärvi (Tiljander, 2003) and the 4000-year long record from Kalliojärvi (Saarni et al., 2016a) show increased minerogenic matter accumulation during a positive NAO. These lakes are located in the region that has been observed to be sensitive to NAO; modern data analysis show enhanced precipitation related to a positive NAO index (Uvo, 2003). In this area, stronger westerly air flows related to positive NAO bring mild and humid air followed by increased snow accumulation and milder winter and spring temperatures. This is consistent with calculated correlation coefficients, which suggest increased minerogenic matter influx during enhanced winter precipitation and mild springs in the records of Lakes Kalliojärvi and Korttajärvi.

Lakes Kuninkaisenlampi and Linnalampi, on the other hand, are located in eastern Finland, which is observed to be a region where winter precipitation is not sensitive to NAO variation (Uvo, 2003). Weak sensibility to NAO could explain the controversial response to winter and spring climate forcing. Furthermore, a 3600-year long record from Lake Kuninkaisenlampi was earlier reported to reflect solar activity changes (Saarni et al., 2016b) with enhanced minerogenic matter accumulation during periods of low solar activity. Atmospheric blocking is suggested as a mechanism mediating solar forcing on catchment dynamics. Intensive atmospheric blocking leads to generally colder spring conditions (Garcia-Herrera and Barripedro, 2006; Brunner at al., 2017), which is in line with the results from Lakes Kuninkaisenlampi and Linnanlampi, where enhanced minerogenic matter accumulation occurs in relation to low May temperatures and longer ice cover duration. Enhanced atmospheric blocking results in decreased winter precipitation (García-Herrera and Barriopedro, 2006; Sousa et al., 2017), which is supported by the negative correlations of minerogenic matter accumulation with winter precipitation and snow water equivalent at all three study sites. The sensitivity for atmospheric blocking was observed to be highest during a grand solar minima (Saarni et al., 2016b), which supports the importance of frost formation in the catchment as a controlling factor for minerogenic matter accumulation. During milder springs, the climate sensitivity through decreased frost formation is weakened. Minerogenic matter accumulation in lakes is also enhanced due to precipitation in spring (Table 4, Figure 4). Rainfall events on May prompts the erosion and transport of fine grained material (Rydberg and Martinez-Cortizas, 2014) that is observed as increased clast transport and is very likely enhanced by the surface run-off on the frozen soil. In addition, precipitation increase the rate of snow melt and it is possible that erosion is simply induced through the increased rate of snow melt as well.

However, it should be noted that Lake Kantele shows a discrepancy compared to the other two lakes on fine-grained tills: a positive correlation between spring temperature and minerogenic matter accumulation was observed (Table 4). This might be an artefact of a stronger winter precipitation-frost development link, although there is no evidence to clarify the difference and a more detailed investigation including on-site hydrological and meteorological as well as sediment trap monitoring would be necessary.

Discrepancies and human interference

The poor correlations between varve characteristics and climatic variables during a certain time period do not necessarily mean that climate does not influence the sedimentation, but reflects the fact that other environmental factors are more influential. Hydrological, meteorological, and varve data were not observed at the same locations because of a lack in monitoring activities and meteorological stations for the small and remote lakes. This fact not only weakens the correlations but also decreases the significance level of the statistical results. Furthermore, several natural factors may decrease the correlation between varve parameters and instrumental climatic data (Perkins and Sims, 1983; Itkonen and Salonen, 1994; Wohlfarth et al., 1998; Tian et al., 2011). Firstly, the long-time series can be hampered by counting errors in varve chronology. Secondly, varve years vary in length, because the thawing date of the lake differs considerably from year to year. Thirdly, the response to climatic forcing is not necessarily linear, but can vary in magnitude leading to poor correlations. Thus, an 11-year running average was used for total winter precipitation to overcome these problems. The temporal extent of the hydrological data available is short, thus preventing the use of smoothed data.

Meteorological data are available approximately for the last hundred years, which coincides with the intensified human activities on lake catchments. Human activities accelerate the rate of erosion (Augustson et al., 2013; Zolitschka et al., 2015), but the scale of increase followed by different actions is difficult to measure. Furthermore, interactions between anthropogenic forcing factors and lake watersheds occur individually for every lake in scale and timing.

Minerogenic lamina reflects erosional processes (Renberg, 1981; Ojala et al., 2013). The spring floods as well as the surface run-off are natural factors that increase catchment erosion. However, human actions, such as forest logging, cultivation, ditching, and infrastructural constructions, enhance erosion as well and very likely temporarily obscure the rate of natural erosion. This is very clear in the case of Lake Linnanlampi, where clastic matter input shows a very sudden and significant erosional peak at AD 1906, and at Lake Kuninkaisenlampi where erosion peaked at AD 1917 (Figure 3), both related to expanding human occupation and building of roads (Eskelinen 1985). Unfortunately, the instrumental records do not extend beyond human disturbance in the catchment areas. Therefore, the possibility of human actions before the erosional events during the 19th and 20th century cannot be excluded and there is a risk that these events can be falsely interpreted as natural ones. However, the sudden erosional peaks related to human actions seem to be short-lived and, although they likely decrease the correlations between varve and climatic parameters for long records, they do not permanently change the response of the lakes to climate forcing after these erosional peaks. This interpretation is supported by the PCA analysis, which revealed no directional trajectory for the lakes with respect to time, suggesting that recent human activities have not changed or suppressed the climatic signal in the lakes. However, a single erosional peak in any lake must always be interpreted with caution. ..

Conclusions

This study presents recent clastic-biogenic varve records from three lakes in eastern Finland characterized by a catchment area with fine-grained tills. The aim was to identify the physical mechanisms that control minerogenic matter accumulation in these small lakes using meteorological and hydrological data and statistical methods. Our results show that minerogenic accumulation is sensitive to winter precipitation and spring temperature variations. However, the catchment characteristics ultimately control the way in which climatic forcing affects minerogenic accumulation. The different responses of each lake to climate parameters underline the importance of understanding lake and catchment processes in detail before using lake records for climate reconstructions. The three studied lake records show clear differences compared to previously studied lakes from areas with other soil types in central and southern Finland. The negative correlation between minerogenic matter accumulation and snow accumulation points to a significant influence of fine-grained tills, that are sensitive to frost formation and, thus, to decreased snow accumulation. The negative correlation with spring temperatures suggests that the lakes in this region are forced by climatically different mechanisms than the lakes in central and southern Finland. In conclusion, using multiple lake records in order to reconstruct past climate parameters could be an advantage. However, even neighboring lakes of similar morphology and catchment areas can reflect different climate signals for reasons that remain to be clarified. Our results highlight the regional differences in climatic responses and underline the importance of understanding the catchment processes in order to assess the mechanisms of climatic forcing.

Acknowledgements

The authors wish to thank Hannu Wenho and Arto Peltola from the University of Turku for technical support. The work was supported by the Maa- ja vesitekniikan tuki ry under Grant no. 31257; Kone Foundation under Grant no. 27-5385; and The Academy of Finland under Grant no. 269834.

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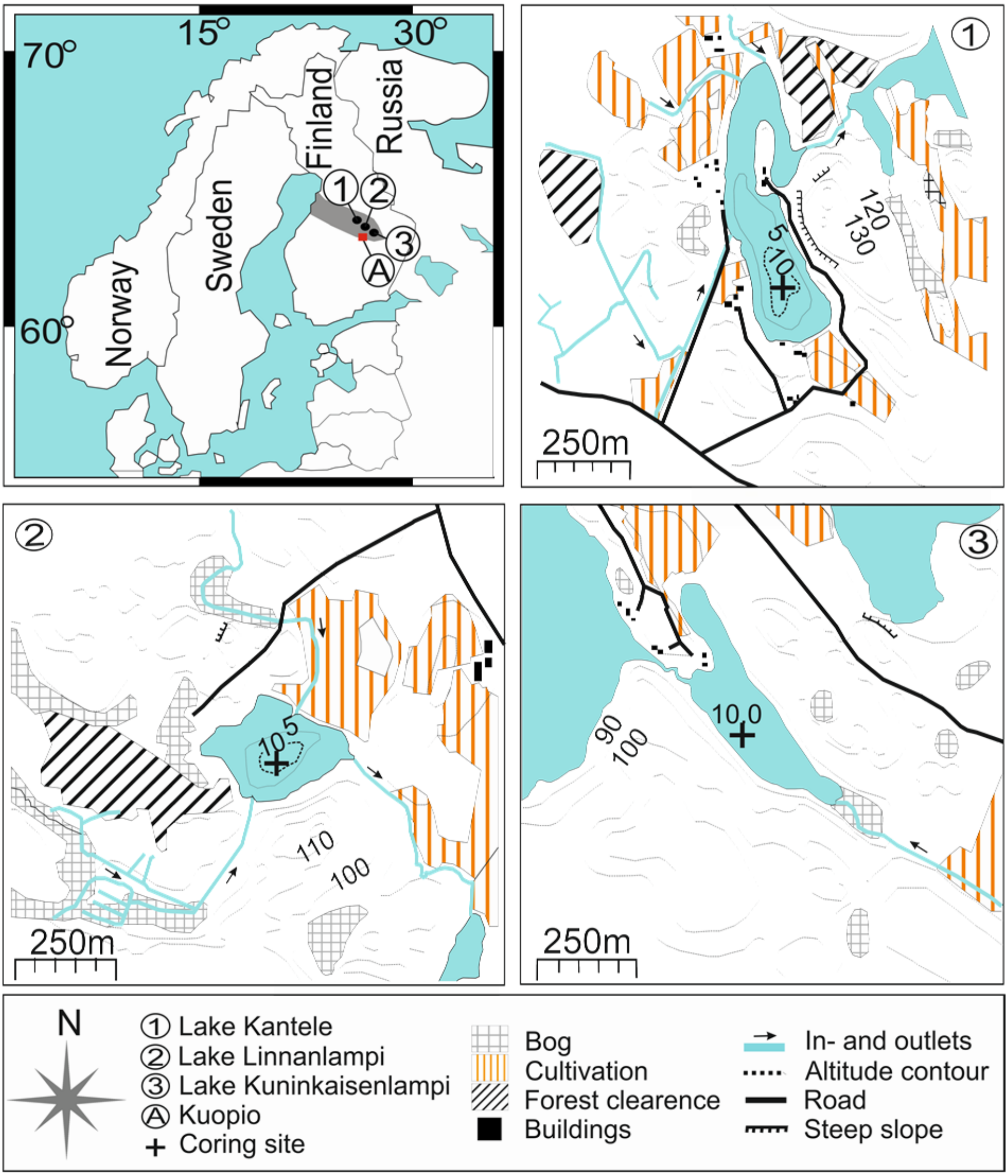


Figure 1. Location of studied lakes and meteorological station of Kuopio (A) in Fennoscandia (upper left). The area with common occurrence of fine-grained tills is shaded in grey. (1-3) Bathymetric maps and the immediate catchments of the studied lakes. A cross represents the coring site.

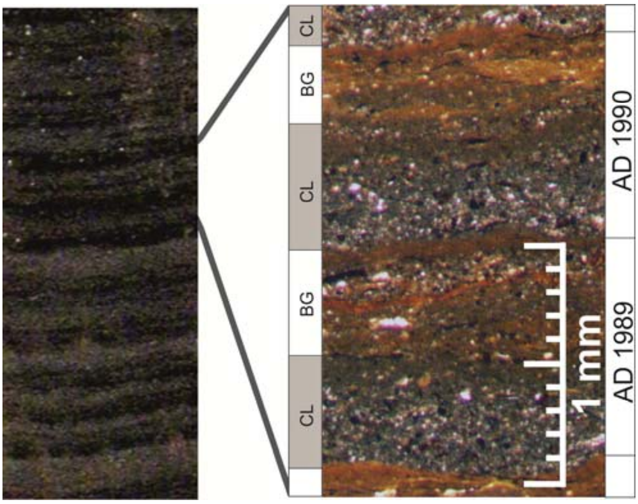


Figure 2. Representative example of clastic-biogenic varves from Lake Linnanlampi. Macroscopic image of the freeze core (left) and microscopic image of a thin section (right). Minerogenic particles in clastic lamina (CL) show graded bedding followed by biogenic matter (BG). Contacts between organic and clastic laminae are very clear.

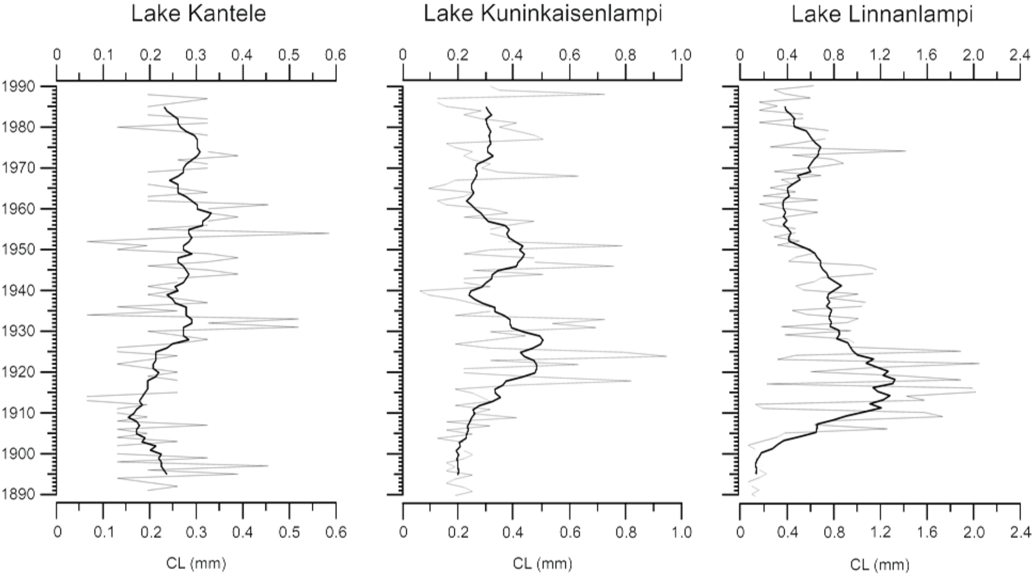


Figure 3. Variation of clastic lamina (CL) thickness for each studied lake. The grey line shows annual variations and the black line the 11-year running average.

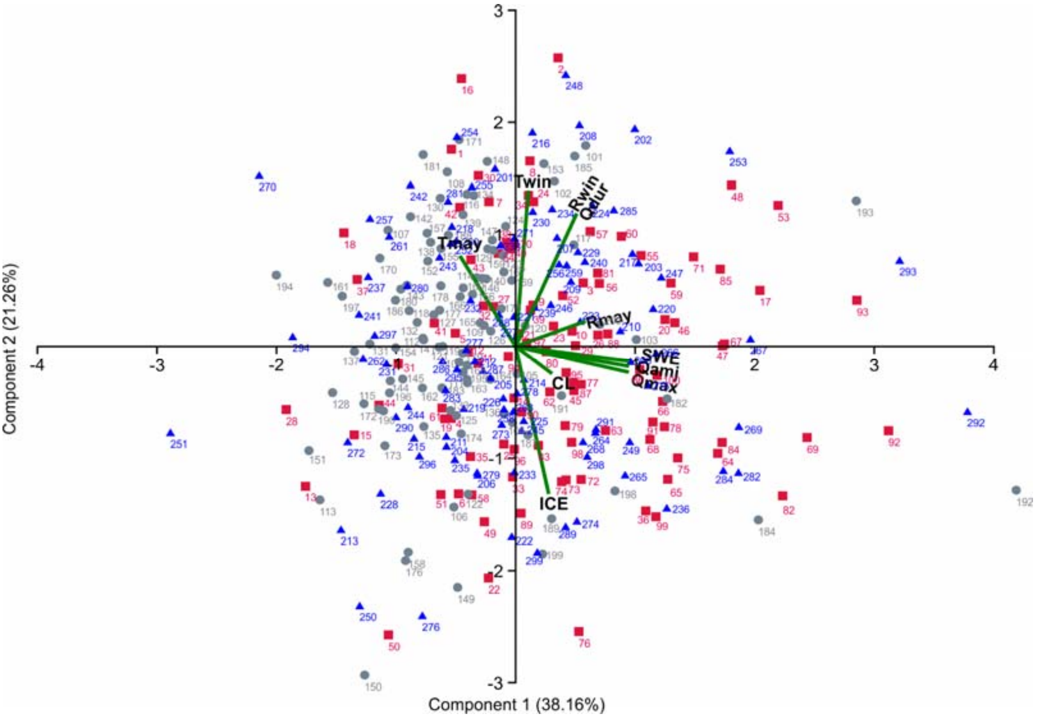


Figure 4. PCA biplot of climatic and hydrological variables and clastic lamina thickness variation (green lines) with sampling sites from Lake Linnanlampi (red squares), Lake Kantele (gray circles) and Lake Kuninkaisenlampi (blue triangles). Sample numbers indicate the sample age as follows: samples 1-100 Lake Linnanlampi, 1 = year AD 1990, 100 = year AD 1890; samples 101-200 Lake Kantele, 101 Year AD 1990, 200 = year 1890; samples 201-300 Lake Kuninkaisenlampi, 201=year AD 1990, 300 = year AD 1890.

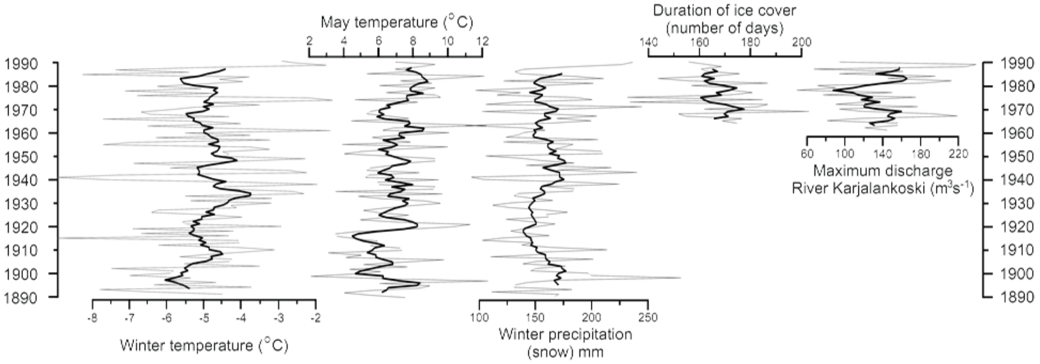


Figure 5. Winter climate variability at Kuopio meteorological station during a 100-year period (1890-1990) and hydrological variability from vicinity of the Lake Kuninkaisenlampi. The grey line shows annual variation and the black line indicates the 11-year moving average.

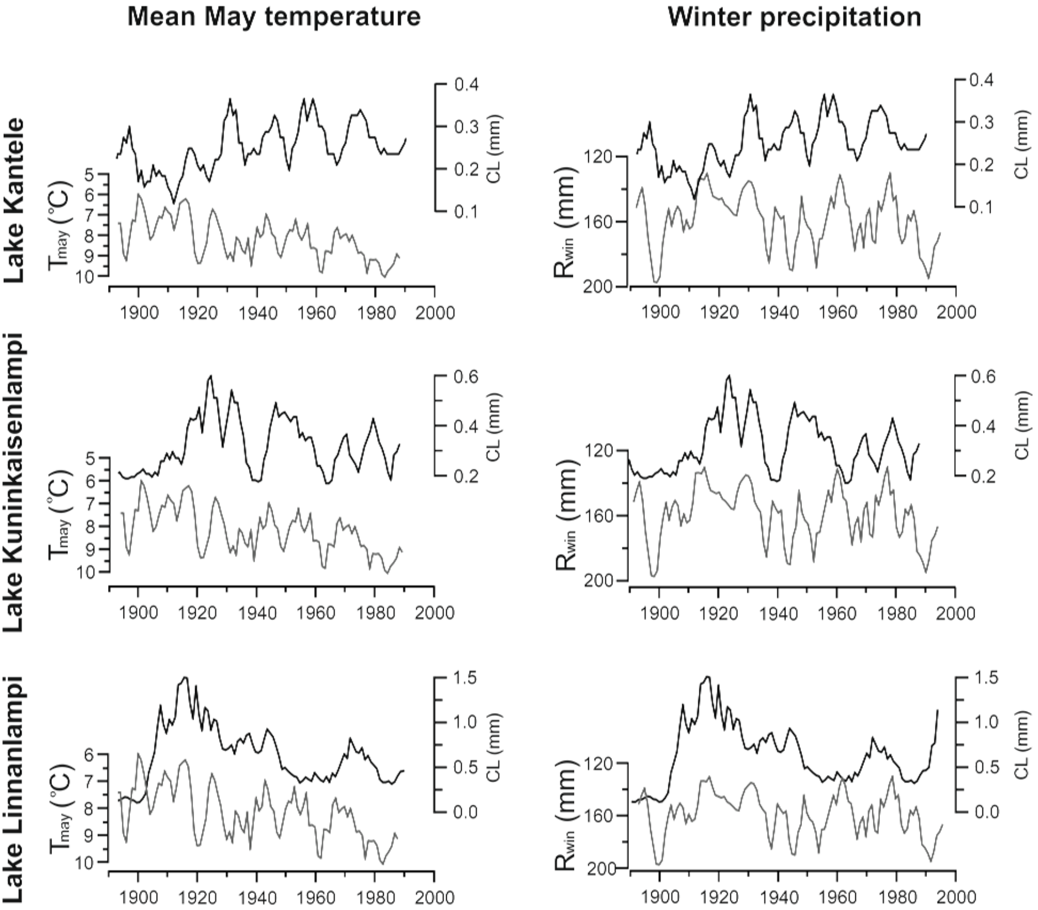


Figure 6. Clastic lamina (CL) thickness variation for each studied lake against mean May temperature (Tmay) and winter precipitation (Rwin), both from Kuopio meteorological station. All data shown as 5-year moving averages. Note inverse axes in Tmay and Rwin.

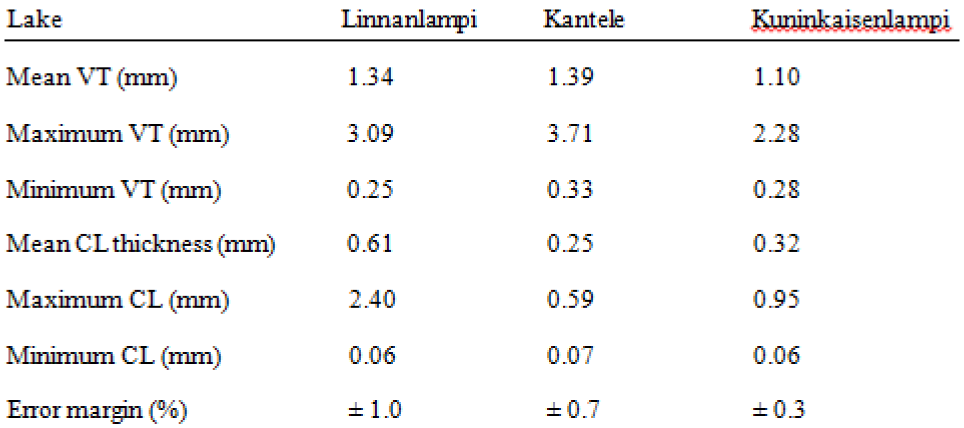
Table 1. Morphometric data of studied lakes and their catchment areas.

Lake	Kantele	Kuninkaisenlampi	Linnanlampi
Location	63°29’N 26°39’E	62°58’N 28°14’E	63°19’N 27°10’E
Lake surface area (km^2)	0.10	0.05	0.05
Catchment area (km^2)	1.0	1.1	9.0
Maximum water depth (m)	12.0	10.1	11.0
Elevation of lake level (masl)	108	82	96
Catchment type	fine-grained till, clay, minor peat formations, bedrock outcrops	fine-grained till, silt, clay, minor peat formations, bedrock outcrops	fine-grained till, clay,minor peat formations, bedrock outcrops

Table 2. Winter climate conditions at the study sites including distances to hydrological and meteorological stations and temporal extent of each data set.

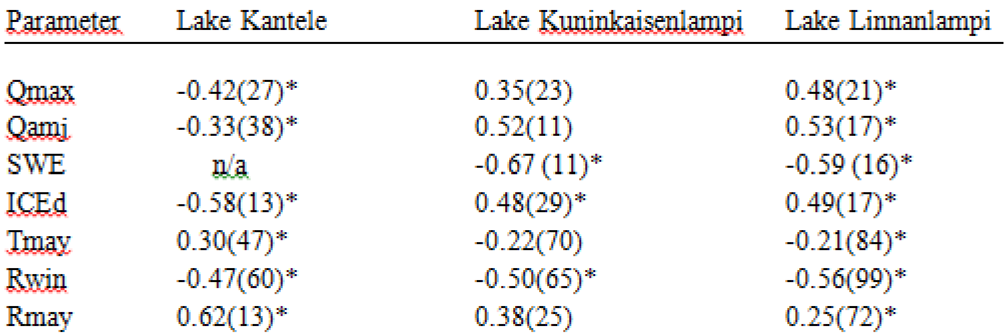
Lake	Kantele	Kuninkaisenlampi	Linnanlampi
Precipitation and temperature data			
Station	Kuopio	Kuopio	Kuopio
Distance to station	85	34	53
Years AD	1890-1990	1890-1990	1890-1990
River discharge data	**River Koivujoki**	**River Karjalankoski**	**River Viannonkoski**
Distance (km),	16	8	10
Years AD	1910-1980	1961-1990	1890-1951
Duration (days)	9-68	5-73	17-69
Annual max. discharge (m^3/s)	1.3-11.6	49-239	48-484
Snow water equivalent data	**Koivujoki**	**Vuotjärvi**	**Viannonkoski**
Distance (km)	17	10	10
Years AD	1961-1980	1949-1990	1946-1990
Snow pack water equivalent (mm)	69-216	85-262	75-228
Duration of the ice cover	**Lake Koivujärvi**	**Lake Kallavesi**	**Lake Maaninkajärvi**
Distance (km)	27	16	24
Years AD	1962-1990	1891-1990	1964-1990
Duration of ice cover (days)	136-210	127-203	127-203

Table 3. The varve characteristics (VT = total varve thickness, CL = clastic lamina thickness) and error margins related to each varve chronology.



Lake	Linnanlampi	Kantele	Kuninkaisenlampi
Mean VT (mm)	1.34	1.39	1.10
Maximum VT (mm)	3.09	3.71	2.28
Minimum VT (mm)	0.25	0.33	0.28
Mean CL thickness (mm)	0.61	0.25	0.32
Maximum CL (mm)	2.40	0.59	0.95
Minimum CL (mm)	0.06	0.07	0.06
Error margin (%)	± 1.0	± 0.7	± 0.3

Table 4. Calculated correlations between clastic matter accumulation (CL) and hydrological and meteorological data. Statistically significant correlations at the confidence level of $p < 0.05$ (marked with an asterisk) and correlations approaching the confidence level $(0.5<p<0.1)$ are considered. Sample size n (number of years) shown in parentheses. Qmax = maximum river discharge, Qamj = mean discharge of flooding season (amj = April-June), SWE = snow pack water equivalent, ICEd = number of days with ice cover, Tmay = mean temperature of May, Twin = mean temperature of winter months, Rwin = precipitation sum of winter months.



Parameter	Lake Kantele	Lake Kuninkaisenlampi	Lake Linnanlampi
Qmax	-0.42(27)*	0.35(23)	0.48(21)*
Qamj	-0.33(38)*	0.52(11)	0.53(17)*
SWE	n/a	-0.67 (11)*	-0.59 (16)*
ICEd	-0.58(13)*	0.48(29)*	0.49(17)*
Tmay	0.30(47)*	-0.22(70)	-0.21(84)*
Rwin	-0.47(60)*	-0.50(65)*	-0.56(99)*
Rmay	0.62(13)*	0.38(25)	0.25(72)*