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ABSTRACT

This dissertation discusses sedimentary varve formation and Late Holocene paleoenvironmental and climatic variation. Varved sediment records from five lakes in central and eastern Finland were studied. Three varve records, 3 000 - 4 000 years long, from the clastic-biogenic sediments of Lake Kalliojärvi and Lake Kuninkaisenlampi and biogenic sediments of Lake Kallio-Kourujärvi were reconstructed. In addition, two short records that cover the last 100 years were constructed from Lake Kantele and Lake Linnanlampi. These lakes were cored after an intensive search for previously unknown varved lakes. Piston and freeze cores of sedimentary sequences were obtained from each lake basin for varve, magnetic and chemical analyses. Sediments were impregnated in epoxy resin and the physical varve properties, which include total varve thickness and laminae thicknesses, were analyzed using either a stereographic microscope under dark field illumination or a digital image analysis technique. Paleomagnetic secular variation of the Earth's magnetic field was measured from Lake Kallio-Kourujärvi, Kalliojärvi and Kuninkaisenlampi sediments and inclination and relative declination were obtained. The major paleomagnetic secular variation features of the records are in agreement with both North Karelian Stack and Fennostack and support the varve dating. The varve data were subjected to statistical analyses in order to study the relationship between hydroclimate and varve characteristics. The results highlight the influence of catchment dynamics in varve formation. Clastic lamina thickness has been previously related to spring flood intensity controlled by snow accumulation. However, this study shows an inverse relationship between snow accumulation and clastic lamina thickness in lakes located in the region of fine-grained tills. This could be explained by the frost sensitivity of fine-grained tills, where enhanced erosion on catchment is interpreted as a result of frost that prevents infiltration of melt waters into the ground. Consequently, in years with deeper ground frost the surface run-off during melting season is increased, thus increasing the amount of catchment derived mineral matter in the lake. The frost formation is strongest during winters with low snow accumulation. The clastic laminae of the Lake Kalliojärvi in central Finland, located in an area dominated by sand moraines, are positively correlated and sensitive to winter precipitation and snow accumulation. Biogenic laminae at the lakes with low trophic status were sensitive to precipitation. Enhanced precipitation not only increases the nutrient transport from the catchment into the lake, but also increases the transportation of terrigenous organic matter. Lake Kalliojärvi record reflects the North Atlantic Oscillation variability, very likely through increased snow accumulation during the positive NAO phase. The long varve record from Lake Kuninkaisenlampi reflects solar activity variation in detail and atmospheric blocking related to cold and less snowy winters would explain this link. Based on the results of this study the catchment characteristics and the region impose a strong control over which climatic forcing the lake is sensitive to.

TIIVISTELMÄ

Tämä väitöskirja esittelee kolme uutta vuosikerrallista eli lustosedimenteistä luotua aikasarjaa myöhäis-Holoseenin aikaisten ympäristö- ja ilmastovaihteluiden ymmärtämiseksi. Yhteensä kolme yli 3 000 vuotta pitkää lustoaikasarjaa tutkittiin, joista Kalliojärvi ja Kuninkaisenlampi, ovat klastis-biogeenisia lustosedimenttejä ja Kallio-Kourujärvi on biogeeninen lustosarja. Lisäksi tutkittiin kaksi viimeiset sata vuotta kattavaa aikasarjaa kahdesta järvestä, Kanteleesta ja Linnanlammesta. Suurin osa näistä aiemmin tuntemattomista lustokerrostumista löytyivät projektin alkuvaiheessa suoritetun intensiivisen etsinnän tuloksena. Kustakin järvestä otettiin useita näytteitä sekä mäntäkairalla että jääsormitekniikalla lustokronologian luomiseksi, lustojen fysikaalisten ominaisuuksien mittaamiseksi sekä kemiallisia ja magneettisia analyyseja varten. Lustojen fysikaaliset ominaisuudet, kuten luston kokonaispaksuus sekä lustorakenteiden paksuudet mitattiin joko digitaalisen kuva-analyysimenetelmän avulla röntgenkuvista tai pimeäkenttävalaistusta ja stereomikroskooppia käyttäen ohuthieistä. Lustokronologian oikeellisuuden vahvistamiskeksi paleosekulaariset vaihtelut mitattiin pitkistä sedimenttinäytteistä, joista inklinaatio- ja deklinaatioheilahdukset laskettiin. Havaitut paleosekulaariset vaihtelut ovat ajallisesti yhdenmukaisia sekä Pohjois-Karjalasta että Fennoskandiasta mitattujen vaihteluiden kanssa. Tilastollisia menetelmiä käytettiin lustoparametrien sekä ilmasto- ja hydrologisten aineistojen välisien riippuvuuksien selvittämiseksi. Tulokset osoittavat, että järven valuma-alueen ominaisuuksilla on suuri vaikutus siihen, kuinka ilmaston muutokset tallentuvat lustoihin. Klastisen lustonosan paksuus ja valuma-alueen eroosion määrä on liitetty aiemmin lumen määrään ja sen sulamista seuraavan kevättulvan voimakkuuteen. Tutkimuksen tuloksena havaittiin kuitenkin, että hienoainesmoreenialueella klastinen lustopaksuus korreloi negatiivisesti lumimäärien ja talvikauden sadannan kanssa. Tämä johtuu todennäköisesti hienoainesmoreenin routaherkkyydestä ja routimisesta, joka on voimakkainta vähälumisina talvina. Sulamiskauden aikainen routa lisää pintavalumaa, jolloin eroosio voimistuu. Biogeenisen lustonosan paksuus sen sijaan riippuu sadannasta erityisesti alhaisen trofiatason järvissä, joissa biogeenistä tuotantoa kontrolloi ravinteiden saatavuus. Runsaat sateet lisäävät ravinteiden kulkeutumista järveen valuma-alueelta, mutta myös terrestrisen orgaanisen aineksen kulkeutumista järveen. Tutkimus osoittaa, että Pohjois-Atlantin Oskillaatio (NAO) kontrolloi merkittävästi Keski-Suomen alueen lumimääriä. Kuninkaisenlammen klastisen lustonosan havaittiin heijastelevan auringon aktiivisuuden muutoksia. Tämä aiheutuu todennäköisesti alhaisen auringon aktiivisuuden aikana vallitsevista ilmakehän paineolosuhteista, jonka seurauksena talvet ovat kylmiä ja vähälumisia.

CONTENTS

LIST OF ORIGINAL PUBLICATIONS

This thesis arose from the original project entitled "Solar forcing in climate change inferred from varved lake sediments" by T.Saarinen funded by Academy of Finland (grant n:o 123724) and is based on the following publications:

I Saarni, S., Lensu, A., Haltia, E., Saarinen, T. Winter climate signal in boreal clastic-biogenic varves; a comprehensive analysis of multiple varved records from 1890 to 1990 AD and instrumental data from eastern Finland. *Manuscript.*

II Saarni, S., Saarinen, T., Lensu, A., 2015. Organic lacustrine sediment varves as indicators of past precipitation changes: a 3,000-year climate record from Central Finland. Journal of Paleolimnology 53: 401-413. *Reprinted with permission from Springer*.

III Saarni, S., Saarinen, T., Dulski, P., 2016. Between the North Atlantic Oscillation and the Siberian high: A 4000-year snow accumulation history inferred from varved lake sediments in Finland. The Holocene 26: 423–431. *Reprinted with permission from Sage journals*.

IV Saarni, S., Muschitiello, M., Weege, S., Brauer, A., Saarinen, T. 2016. A Late Holocene record of solar-forced atmospheric blocking variability over Northern Europe inferred from varved lake sediments of Lake Kuninkaisenlampi. Quaternary Science Reviews 154:100–110. *Reprinted with permission from Elsevier*.

ABBREVIATIONS

AMO	Atlantic Multidecadal Oscillation
AD	Anno Domini
B	Biogenic varve type
BL	Biogenic lamina
BP	Before present i.e. years before the calendar year 1950
CB	Clastic-biogenic varve type
CL	Clastic lamina
DS	Dark sum
ENSO	El Nino Southern Oscillation
FC	Freeze corer
GSL	Growing season lamina
ICE_d	Duration of the ice cover
IPCC	International Panel on Climate Change
KAL	Lake Kalliojärvi
KKJ	Lake Kallio-Kourujärvi
KNT	Lake Kantele
KUN	Lake Kuninkaisenlampi
LIA	Little Ice Age
LIN	Lake Linnanlampi
LS	Light sum
m a.s.l.	Meters above the present day sea level
MCA	Medieval Climate Anomaly
MWP	Medieval Warm Period
NAO	North Atlantic Oscillation
NRM	Natural remanent magnetisation
PSV	Paleomagnetic secular variation
Q	River discharge (m^3/s)
Q_{amj}	Mean river discharge of spring (April, May, June)
Q_{max}	Maximum river discharge
Q_{dur}	Duration of the flood event
R	Precipitation (mm)
R_{ann}	Annual precipitation
R_{gs}	Growing season precipitation
R_w	Winter precipitation
SC	Snowcower
SWE	Snow water equivalent (mm)
T	Temperature (°C)
T_{gr}	Growing seasontemperature
T_{may}	Mean temperature of May
T_w	Winter temperature
TSI	Total Solar Irradiance
UV	Ultra violet
VT	Varve thickness
WL	Winter lamina
μ-XRF	Micro x-ray fluorescence

1. INTRODUCTION

1.1 The need for paleoclimatic reconstructions

The climate has undergone great changes throughout the Earth's history, in fact, change is an intrinsic feature of the climate (Zachos, 2001; Strand et al., 2008). Plate tectonics operate on time scales of hundreds of thousands to millions of years and control the movement of continents, pathways of ocean currents, formation of mountain belts and volcanic activity, which collectively have a major influence on the Earth's climatic history over long time scales. The natural variations in the Earths' orbit, on the other hand, are responsible for pacing the cyclic climatic variations of 20 000-100 000 years (Zachos, 2001). These slow but consistent changes together with the following feedback mechanisms within the Earth's system are responsible for glacial-interglacial cycles that characterize the Quaternary period. The Holocene, a geological epoch that begun at 11 700 BP (Cohen et al., 2013), is a warm interglacial, characterized by climatic conditions that are relatively stable from a geological perspective. However, this does not mean that the Holocene climate would not have experienced significant variation as well (Magny, 2004; Mayewski et al., 2004). On shorter time scales the climate is forced by variation in solar activity, volcanic activity, the concentration of greenhouse gases in the atmosphere, and multiple feedback mechanisms that lead to fluctuations in atmospheric and marine circulation systems. Thus, many abrupt changes in the northern high latitudes are known to have occurred during the Holocene (Magny, 2004; Mayewski et al., 2004) such as the 8.2 event (Alley et al., 1997; Morrill and Jacobsen, 2005), the Medieval Warm Period (MWP) also known as the Medieval Climate Anomaly (MCA) (Lamb, 1965; Hughes and Diaz, 1994; Briffa, 2000; Bradley et al., 2003; 2016), and the Little Ice Age (LIA) (Matthews and Briffa, 2005; Mann et al., 2009). These rapid climatic changes show that through numerous feedback mechanisms, many of which are not fully understood, the direct influence can be amplified.

Human activity can be considered geologically recent but it has had a profound impact on the Earth's system. In fact, human activities now occur globally and are the major cause of most contemporary environmental changes. This has prompted discussion of the existence of a new geological epoch called the Anthropocene (Crutzen, 2002; Lewis and Maslin, 2015). Multiple events have been suggested to mark the onset of the

Anthropocene. These suggestions range from the extinction of megafauna, which commenced during early Holocene period and the initiation of anthropogenic emissions of greenhouse gases through the Industrial Revolution, and the atomic era of the 1960s (Lewis and Maslin, 2015; Ruddiman et al., 2015). CO_2 and methane concentration in the atmosphere have increased already during the mid-Holocene due to anthropogenic land cover changes (Ruddiman et al., 2003; Kaplan et al., 2011) and early rise farming (Ruddiman et al., 2008; Fuller et al., 2011). Due to increased anthropogenic emissions of greenhouse gases into the atmosphere, the climate is also currently undergoing a human induced change (International Panel on Climate Change (IPCC) 2013). The globally averaged land and ocean surface temperatures have experienced a warming of 0.85°C over the period from AD 1880 to 2012 (IPCC, 2013). To set the present warming in context, it is necessary to know the range and rate of past climatic changes in a spatial and temporal respect. Furthermore, in order to understand and predict climate change it is essential to understand the past climatic variability even on a seasonal and regional scale.

Climate models simulate the response of the climate system to the change of chosen variables. Modeled scenarios are tested using past events in order to constrain models and to improve the reliability of the models' predictions. The ability to predict climate change includes understanding the numerous feedback mechanisms that link the measured change in the driving force to the observed change in the climate. For example, an approximately 0.1% variation in total solar irradiance (TSI) has been measured related to the 11-year Schwabe cycle (sun spot cycle) which is accompanied by an 0.1-0.2 °C fluctuation in global average surface temperatures (Lean et al., 2005). These small temperature variations are not sufficient to explain the solar imprint in past climate records, yet climate proxy records that reveal this cyclic variability exist all around the world (Bond et al., 2001; Hodell et al., 2001; Wang et al., 2005; Vonmoos et al., 2006; Haltia-Hovi et al., 2007; Martin-Puertas et al., 2012; Paper IV).

There is a strong need to further improve the climate models. At the moment, for example, current climate models cannot reproduce the amplitude nor timing of the MCA warming (Lüning et al., 2016; IPCC, 2013) that is reported in the vast number of proxy records all around Europe (Lüning, Medieval Warm Period–electronic map). The poor model performance can be improved with a more detailed network of spatial and temporal observations of modern and past climate. The network of meteorological stations has expanded and become denser during the previous decades, and presently covers even the remotest places on Earth. The technical equipment has been improved and become more accurate. The satellite era enables exact measurements of global winds not only in the troposphere but also in stratosphere as well as monitoring the solar activity variations and global surface temperatures (Lean et al., 2005). Data from meteorological stations and satellites have greatly increased our understanding of the climate.

The earliest temperature measurements in Finland began in mid- 18th century (Vesajoki and Holopainen 1998) but the extensive network of meteorological stations, recording daily temperature and precipitation, was not constructed before the late 19th century. The historical records describing, for example, the harvest dates (Menzel, 2005), the beginning of the sailing season and ice conditions at the ports of Northern Europe (Koslowski and Glaser, 1999; Brázdil et al., 2010; Leijonhufvud et al., 2010) extend as far back as the sixteenth century. However, the written records are subjective descriptions and often fragmented both temporally and spatially. Furthermore, the Sun and the climate system undergo long term changes that cannot be assessed within the short time period covered by measured or historical data. The information of the climatic variations beyond the instrumental records is crucial and can only be gained using indirect methods, so called proxy records, such as ice cores, tree-rings, marine and lake sediments.

1.2 Varves as proxy records

Dating paleoclimatic records is a very important aspect of all paleoenvironmental research. Only precise and accurate dating allows comparison of the proxy records from all around the world in order to build a global picture of the past climatic variation and to determine leads and lags in the interregional response to climate change. Annually laminated i.e. varved sediments form at the bottom of a water body as a result of the climatic seasonal cycle (Renberg, 1981; O'Sullivan 1983, Saarnisto 1986; Zolitschka et al., 2015; Schimmelmann et al., 2016). The altering climatic conditions between the seasons cause changes in sedimentation, and in the type of sedimentary material accumulating on the lake bottom. As a result, the seasonal cycle is imprinted as visibly discernable laminae in varves, and incremental dating is enabled. The seasonal resolution makes varve records one of the most detailed terrestrial archives of past climatic and environmental change. The high temporal resolution of varve records allows reconstructions of seasonal conditions, robust dating, and thus comparability with reconstructions from other paleoclimatic proxies such as tree rings, stalagmites, pollen and microfossil records (Brauer, 2004; Brauer et al., 2009; Zolitschka et al., 2015). A dating uncertainty of around 2-3% is common in varved sediment records, although in a very good and well preserved varve sequence the uncertainty can be even as low as around 1% (Ojala et al., 2012). Nevertheless, using an additional, independent dating method is required to test the accuracy of the varve chronology and assure the absence of hiatuses or erosional events within the varve record (Ojala et al., 2012).

In addition to the precise dating, the potential temporal extent of the varve record is of great value. The varve records may reach thousands or even tens of thousands of years back in time. The longest continuous varve records studied, so far, are the 14 570-year long record from Lake Van, Turkey (Landmann et al., 1996), the 15 000-year record from Lake Sihailongwan, China (Schettler et al., 2006), the 23 220-year long record from Lake Holzmaar, Germany (Zolitschka et al., 2000) and the 52 800-year chronology from Lake Suigetsu, Japan (Kitagawa and van der Plicht, 1997; Bronk Ramsay et al., 2012). The longest continuous marine varve record, so far, is a 14 000-year long record found in the Cariaco Basin in the Caribbean Sea off Venezuela (Hughen et al., 1996). In Fennoscandia, the records may cover the entire Holocene, having formed continuously since the initiation of the lake after the Fennoscandian ice sheet retreated from the area around 10 000 years ago (Ojala and Alenius, 2005; Zillén et al., 2003). Indeed, the longest Fennoscandian record studied covers the 10 000-year period from the early Holocene to the present day. This record is from Lake Nautajärvi, in southern central Finland (Ojala and Alenius, 2005).

The significant advantage of varve records is their seasonal resolution, which enables the study of different seasonal variations separately. It is possible not only to calculate the flux rates of any sedimentary constituent present in varves, but also to record chemical, physical and microfossil variation in very short time intervals, which results in a potential for multi-purpose and diverse use of varve records. The varves commonly occur in lake and marine basins at high and mid latitudes where laminae form as consequence of seasonal contrasts. However, it is possible that the potential and occurrence of varves in mid to low latitudes is underestimated due to lack of systematic attempts on finding varved sediments (Zolitschka et al., 2015; Schimmelmann et al., 2016). Varves and biogenic fossils incorporated in them can be used to investigate winter-climate and growing-season signals separately from the same site, as has been done for Lake Nautajärvi in Finland (Ojala and Alenius, 2005) and Lake Silvaplana, Swizerland (Leemann and Niessen, 1994; Blass et al., 2007; Larocque-Tobler et al., 2010).

The suitability of varved sediments for paleoclimatic and environmental reconstructions is manifested in the systematic syrveys in order to find undiscovered varved lakes (Larsen and MacDonald, 1993; Larsen et al., 1998; Ojala et al., 2000; Zillen et al., 2003; Tylmann et al., 2013), and in the increase in the number of published research papers during the past decades. Results from varved proxy records have been successfully used for studying the Holocene variation in solar activity (Berggren et al., 2010; Martin-Puertas et al., 2012; Czymzik et al., 2015; Ojala et al., 2015; Paper IV), flood frequency (Swierczynski et al., 2012; Amann et al., 2015; Czymzik et al., 2016), past temperature variation (Moore et al., 2001; Blass et al., 2007; Ojala et al., 2008), glacial activity (Ohlendorf et al., 1997; Striberger et al., 2011), and precipitation (Lamoureux, 2000; Lamoureux and Gilbert, 2004; Romero-Viana et al., 2011; Paper II). The studies have increasingly focused on atmospheric circulation patterns (Brauer et al., 2008; Martin-Puertas et al., 2012; Ojala et al., 2015) such as El Niño Southern Oscillation (ENSO) frequencies reported from a Chilean lake (Boës and Fagel, 2008) and marine varves off California (Anderson et al., 1990; Nederbragt and Thurow, 2005), Asian monsoon variability (Yamada et al., 2010) and NAO/AMO variability from Iceland (Ólafsdóttir et al., 2013) and NAO variability from many sites in continental Europe (Romero-Viana et al., 2008; 2011; Mangili et al., 2010; Zahrer et al., 2013). Varves have recorded the late glacial climate fluctuations (Zolitschka et al., 2000) and the Younger Dryas cold event at the termination of the last glaciation (Landmann et al., 1996; Brauer et al., 2008). Marine varves from the Cariaco Basin off Venezuela were used to shed light on the collapse of the Mayan civilization (Haug et al., 2003).

Varves have also been found in the restricted basins of the Baltic Sea from the marine and estuary environments. Varves from the River Ångerman estuary (eastern coast of Sweden) had already been studied in the early 20th century (Petterson, 1996) while recent varves have been reported in the Gulf of Finland in several locations where their formation has been related to increased anoxia (Kotilainen et al., 2007; Jokinen et al., 2015). The minerogenic component in the Ångerman river estuary has been reported to reflect maximum spring flood events (Cato, 1985; Wohlfarth et al., 1998; Sander et al., 2002), while the deposition of the lithogenic laminae found in the Archipelago and Gulf of Finland (Baltic Sea) has been suggested to be caused by resuspension of terrigenous material concomitantly with increased cyclonic activity and prevailing anoxic conditions (Jokinen et al., 2015).

These studies of varved sediments, among many others, have increased our understanding of detailed temporal and spatial environmental and climatic changes occurring on various scales. Furthermore, they have shed light on the chain of feedback mechanisms operating behind the changes in sedimentation, and, have provided a valuable tool in order to gain a comprehensive understanding of climate mechanisms.

1.3 Varved lake sediments and their occurrence in Finland

The varve formation is controlled by catchment geology and climate processes which control, runoff and erosion, soil formation, mineral and nutrient availability, and the extent of the plant cover in the lake-catchment system. While the geology remained nearly unchanged during the Late Holocene, most of the variation in the sedimentation primarily reflects climatic and more recently human induced changes (Figure 1). Lacustrine sedimentary sequences contain proxy-environmental information from hydrological-, productivity- and decompositional variation. Small lakes with restricted catchments are very sensitive to local catchment and climate changes and thus provide a basis for high-resolution studies (Brauer, 2004; Haltia-Hovi et al., 2007; Brauer et al., 2009, Zolitschka et al., 2015).

Varves can be found in lacustrine and marine basins where certain criteria are met. Formation of varves requires seasonal cycles that control the character of the depositing sediment while a pre-condition for the preservation of the varve structure is the absence of post-depositional disturbance (Renberg, 1981; O'Sullivan, 1983). Long varve records can only be preserved if no erosional events occur and prevailing anoxic conditions protect the sediment from bioturbation. In addition to bioturbation, sediment mixing can be caused by slumps, turbidite flows and bottom currents that are controlled by the basin bathymetry. Resuspension is controlled not only by bathymetry, but also by wave and ice activity (Ojala et al., 2000; Zolitschka et al., 2015).

Several different varve types can be recognized in the lakes with a boreal environment (O'Sullivan, 1983; Zolitschka et al., 2015). The most commonly found varve type in a boreal setting are the clastic-biogenic varves which are formed only in the presence of fine-grained minerogenic matter in the catchment area (Renberg, 1981; Ojala et al., 2000; Brauer, 2004). Other varve types found in the boreal zone are biogenic varves and biochemical varves (O'Sullivan, 1983; Zolitschka et al., 2015). Biochemical varves exist in areas of carbonaceous bedrock, where the dissolved calcite is precipitated onto the lake floor as a consequence of seasonal variations in water stratification and pH (Brauer, 2004). Such sediments are frequently encountered, for example, in the European Alps (Lotter and Lemcke, 1999; Brauer et al., 2009) and northern Poland (Tylmann et al., 2013), but are not found in Finland due to lack of calcite rich bedrock. Biogenic varves are formed as a consequence of different groups of algae growing from the spring to autumn season at the sites where clastic matter is not transported to the lake (Brauer, 2004; Paper II).

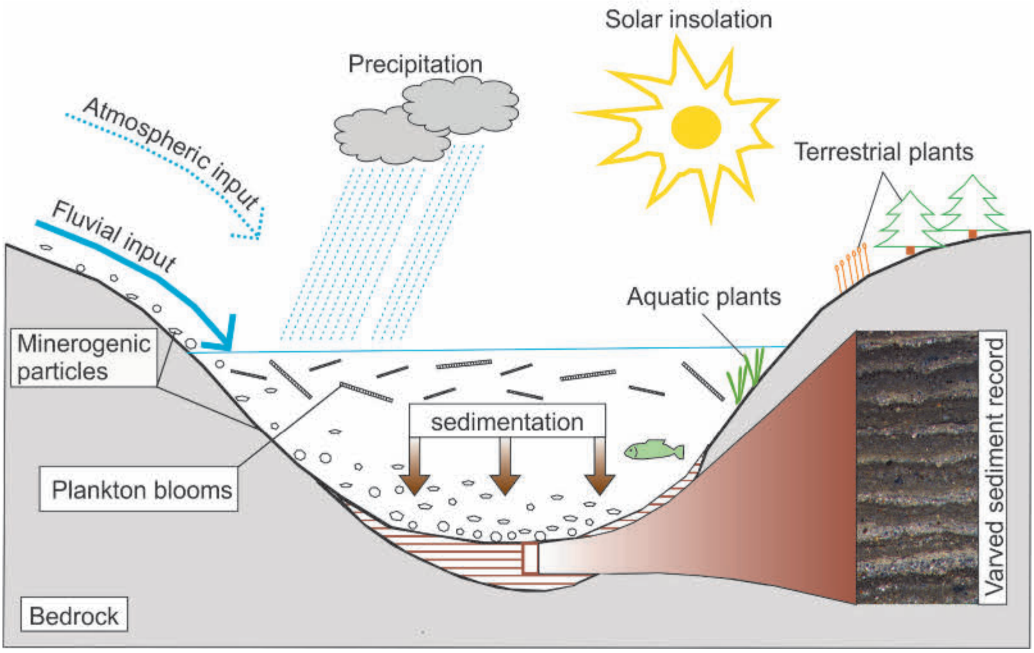

Figure 1. Varve formation is controlled by geology, climate, and human activities. Fluvial input transports minerogenic particles, organic matter and dissolved nutrients that enable autochthonous production. Atmospheric input includes minerogenic particles and biogenic matter such as leaves and pollen. Catchment erosion is controlled by the variations in seasonal runoff and terrestrial plant cover.

The glacially carved environment in Finland is optimal for varve studies due to numerous occurrences of lakes. In Finland, there are 187 188 lakes (surface area > 0.05 ha; Raatikainen and Kuusisto, 1990). The glacially carved lakes are quite deep related to their surface area, most of the lakes are less than 10ha. Furthermore, the seasonal cycle of the present boreal climate is favorable for varve formation due to the strong contrast between winter and summer season. During the post-glacial development of the Baltic Sea, central and eastern Finland were largely submerged under previous brackish and freshwater stages (Eronen and Haila, 1990), which resulted in the deposition of easily erodible fine minerogenic sediments in the catchments of the subsequently isolated lakes.

1.4 The value of Finnish varve records

The systematic study of Finnish varve records started in the 70's with the pioneering work of Matti Saarnisto (Saarnisto 1975; 1985; 1986; Saarnisto et al., 1977) and Mirjami Tolonen (Saarnisto et al., 1977; Tolonen, 1978). Since then, more than 20 Finnish post-glacial varve sequences each covering more than 2000 years have been studied, and a further ten varve sequences, which are shorter or whose total extent is yet unknown have been investigated (Ojala et al., 2000). Long varve records have been reported, for example, from Lake Korttajärvi (Tiljander et al., 2003), Kortejärvi (Haltia-Hovi et al., 2010a), Nautajärvi (Ojala and Alenius, 2005), Heinänlampi and Suurjärvi (Grönlund, 1991), Lehmilampi (Haltia-Hovi et al., 2007), Ahvenainen (Tolonen, 1978), Lovojärvi (Saarnisto et al., 1977), Pohjajärvi (Saarinen, 1998), Heinälampi (Sandman et al., 1990), and Alimmainen Savijärvi (Ojala et al., 2005). The earliest studies were aimed at describing the varve structure and understanding the varve formation processes (Saarnisto et al., 1977; Tolonen, 1978; Simola and Uimonen-Simola, 1983), as well as assessing the use of varve dating in sedimentary research (Tolonen, 1980; Sandman et al., 1990) and evaluating their applicability in paleoenvironmental (Simola, 1983; Simola and Uimonen-Simola, 1983; Sandman et al., 1990; Grönlund and Asikainen, 1992) and paleoclimatological studies (Saarnisto et al., 1977). The most recent studies of varve, including the ones presented in this thesis, are built on the knowledge gained from these pioneering works. The varved sediments have, for example, been proven to be excellent proxy records for studying the history of environmental pollution (Tolonen and Jaakkola, 1983; Meriläinen et al., 2010; 2011). The varves have been used as a dating method in palynological studies with archaeological and paleoenvironmental interests (Tolonen, 1978; Alenius, 2007; Kuosmanen et al., 2016). Varve chronologies have also been used in Finland and Sweden in dating the paleomagnetic secular variations and relative paleointensity of the Earth's magnetic field (Saarinen, 1998; Ojala and Saarinen, 2002; Ojala et al., 2005; Snowball et al., 2007; Haltia-Hovi et al., 2010b).

The value of varve records for investigations of past short-term climatic variation has been recognized and an increasing number of varve records have been studied in this respect (Landmann et a., 1996; Tiljander et al., 2003; Lamoureux and Gilbert, 2004; Ojala et al., 2005; 2015; Haltia-Hovi et al., 2007; Brauer et al., 2008; 2009; Larocque-

Tobler et al., 2010; Striberger et al., 2011; Zahrer et al., 2013; Czymzik et al., 2016). These records have revealed short-term variations in climate during the past few thousand years and they have shed light on mechanisms behind the varying climate providing a very important aspect for the global climate studies. The studies of boreal clastic-biogenic varves have shown that varve formation is sensitive, especially to a winter climate, and the minerogenic clastic accumulation on the lake floor reflects increased river discharge during the spring snow melt season. The clast accumulation is thus a sensitive indicator of the natural winter and spring climate, although the more recent effect of increased human-induced erosion on lake sedimentation was pointed out in early studies (Simola, 1983). The future climate scenarios include an increasing temperature, precipitation, and surface runoff in Finland during the present century (IPCC, 2013). Furthermore, the winter season changes are expected to be larger than the summer season changes (IPCC, 2013). This will have a significant influence on the duration of ice and snow cover, and the amount of snow, which are important feedback mechanisms in the climate system, but also have a strong environmental and socio-economic aspect. Against this background, it is important to understand the variability of winter climate, the background and mechanisms of altering winter conditions, and the scale of the natural variation of winter climate, to be able to predict and adjust to the future change. Past analogues such as the Medieval Climate Anomaly (MCA) can be used to better assess the climate variability. Varved sediments are suitable for this purpose, not only because of their small dating uncertainty but also because of their seasonal resolution, which enables the study of winter and summer conditions separately.

The Finnish varve records are not only of regional importance, but also provide important information for a better understanding of the global climate system. There are thousands of small lakes in central and eastern Finland, which are easy to access, yet not disturbed by significant human activity until the 16th century (Soininen 1961; Orrman, 1991). On the contrary, in many places in Europe human actions have had a considerable influence on sedimentation much earlier (Ralska-Jasiewiczowa and Geel, 1992; Magny, 2004; Dotterweich, 2008). The rural areas in Siberia and Arctic Canada, on the other hand, are free from significant anthropogenic disturbance but can be accessed only by large and expensive helicopter operations. Yet numerous varved lakes have been found and investigated in the Arctic Canada (Lamoureux and Bradley 1996; Zolitschka, 1996; Lamoureux and Gilbert, 2004; Cuven et al., 2010). Finland is located between the 60°N and 70°N latitudes in the boreal and sub-Arctic climatic zone. Due to large seasonal differences and the small sizes of the lakes and their catchments many boreal lakes in Finland are very sensitive to climate variation. The strong teleconnections between atmosphere, world oceans, and continents link the regional climate to global atmospheric circulation patterns that are altered due to numerous mechanisms such as variation in solar irradiation, thermohaline circulation and air-sea interactions. Thus, a small remote boreal lake can add a piece of meaningful information for entire field of climatic studies.

1.5 Objectives

This study arose from the need to better understand the climate not only in a temporal but also in a spatial respect. That is why the project started with a field operation aiming to find lakes containing previously unknown varved sediments. From the 23 varve lakes discovered, four were chosen for detailed inspection due to their high varve quality. Three lakes, Lake Kallio-Kourujärvi (found during earlier project; Ojala et al., 2000), Lake Kalliojärvi and Lake Kuninkaisenlampi were chosen for the purpose of constructing long varve chronologies extending more than 3000 years back in time. In addition, Lake Linnanlampi and Lake Kantele were used to study recent 100-year variation with respect to meteorological data, in order to better understand how well the climate signal is captured by varves in lakes with different catchment characteristics and geographical location.

Key objectives of this study were to better understand past climate and solar forcing, how different lakes with variable catchments respond to climatic forcing and how their sediments record regional changes in past climate and environmental change. The records were compared with meteorological and hydrological data in order to understand the importance of various catchment types and the region regarding sensitivity to climate variations.

2. REGIONAL SETTING

2.1 Study sites

The study region (6980 km^2, 62°33'N – 63°29'N, 25°22'E – 28°14'E) consisted of study sites located in central and eastern Finland (Figure 2). The study sites included the five small dimictic lakes (Table 1) and the nearest meteorological and hydrological observation points. The Lake basins were formed after the Weichselian ice sheet retreat (Saarnisto, 2000). Lake Kalliojärvi and Lake Kallio-Kourujärvi, at elevated locations (121 and 117 m a.s.l, respectively) were probably isolated during the Ancylus Lake regression more than 9 500 years ago (Eronen and Haila 1990; Saarnisto, 2000; Pajunen 2013). The majority of the lake Kallio-Kourujärvi catchment was supra aquatic at all times (Eronen and Haila, 1990) and the hills of the Lake Kalliojärvi catchment area were supra aquatic as well (Eronen and Haila, 1990). The isolation of Lake Kantele, Kuninkaisenlampi and Linnanlampi occurred considerably later from the large water body of Lake Suursaimaa. Due to uneven isostatical uplift, the flow direction of this ancient river system changed around 6 5000 BP (Hakulinen, 2009). Consequent bifurcation and lowering of the water level induced isolation of the new lakes around 6000 years ago, very likely including the Lake Kantele, Kuninkaisenlampi, and Linnanlampi basins (Saarnisto 2000; Hakulinen, 2009). At 4 000 years ago, the Baltic Sea basin reached the Littorina Sea stage and isostatic uplift had already reached the point where the present flow direction of lake systems in central and eastern Finland were stabilized (Hakulinen, 2009).

2.1.1 Lake Kallio-Kourujärvi

Lake Kallio-Kourujärvi is located at an altitude of 117 m a.s.l. in the municipality of Suonenjoki, central Finland (62°33'N, 27°00'E). Due to the elevated location, the majority of the lake catchment was supra aquatic after the Weichselian ice sheet retreat (Eronen and Haila, 1990). At present, Lake Kallio-Kourujärvi is surrounded by steep hills, forests and mires. There are no permanent human settlements in the vicinity of the lake. The catchment is composed of Quaternary sand moraines, sand formations, Carex and Sphagnum peat and bedrock outcrops (Maankamara, DigiKP). The bedrock is composed of plutonic rocks, mainly granites (Bedrock of Finland, DigiKP).

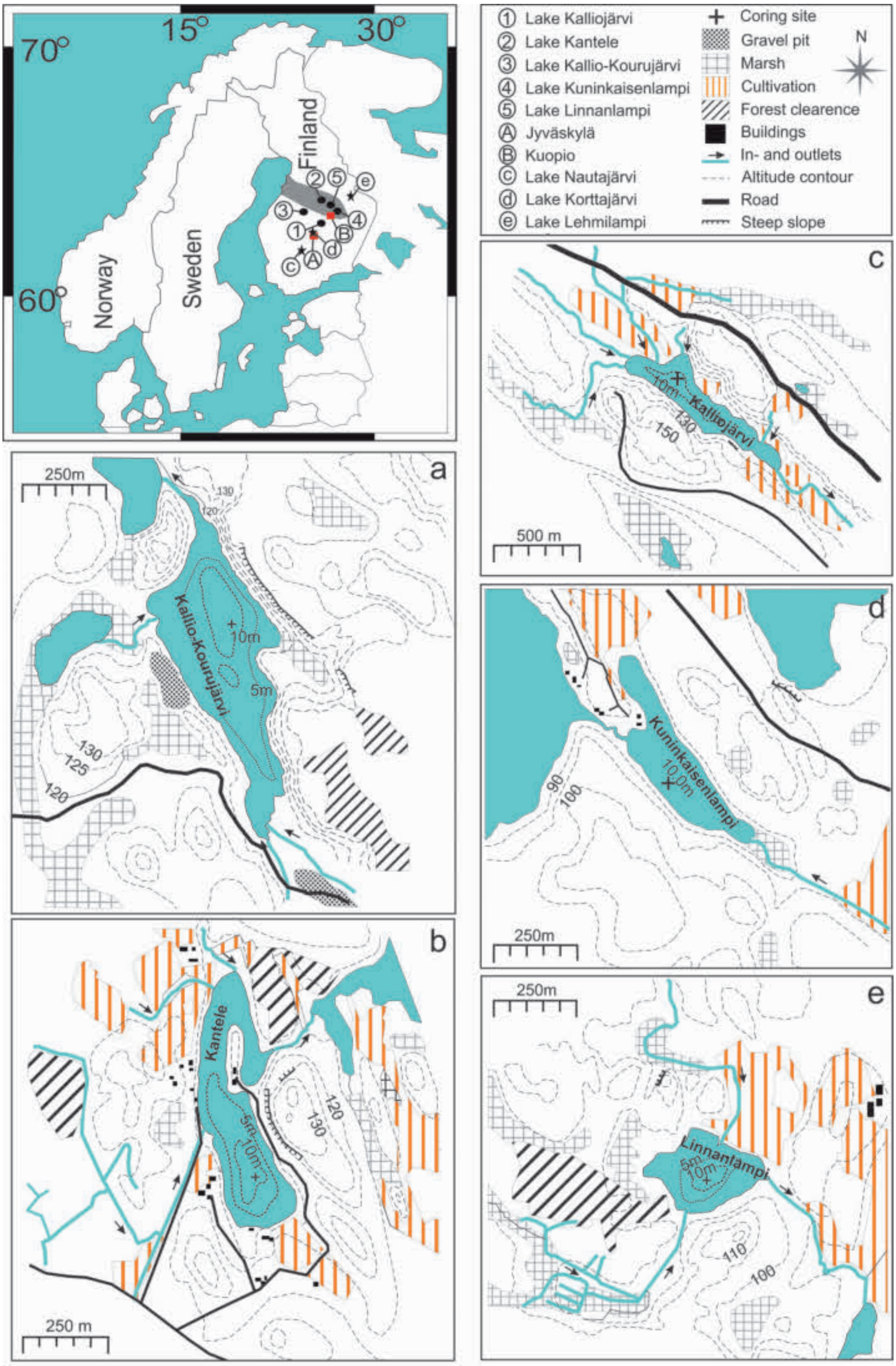

Figure 2. A general map showing the location of the studied lakes (circles) and the nearest meteorological stations (squares) and the previously studied varved lake records (stars). The area with common fine-grained tills is shaded with grey color (after Lintinen, 1995). The figures a-e show a schematic description of the catchment of each lake

Lake Kallio-Kourujärvi is an oligotrophic and dimictic lake (HERTTAdatabase). At present, the elongated lake has a maximum water depth of 11 m, a surface area of 0.13 km^2, and a drainage area of approximately 10 km^2, with a catchment of 1.5 km^2 (Figure 2, Table 1). Three inlets, two in the southern end and one in the western side of the lake transport water, humic substances, organic debris and sediments into the lake. The only way out is an outlet at the northern end.

2.1.2 Lake Kalliojärvi

Lake Kalliojärvi (Figure 2) is located at an altitude of 121 m a.s.l. in the municipality of Viitasaari, central Finland (63°13'N, 25°22'E). Nowadays, Lake Kalliojärvi is surrounded by forests, mires and some cultivated land. There is no permanent residency in the lake catchment. The catchment is composed of sand moraine, Carex and Sphagnum peat and bedrock outcrops (Maankamara, DigiKP). The bedrock is composed mainly of plutonic rocks such as granites, granodiorite and gabbro (Bedrock of Finland, DigiKP).

Lake Kalliojärvi is a eutrophic and dimictic lake (HERTTA database). The elongated lake has a maximum water depth of 12.3 m, a surface area of 0.15 km^2, a drainage area of 9.7 km^2 and a catchment of 6.3 km^2. The two major inlets are at the north-western end of the lake, and there is a major outlet at the south-eastern end.

Table 1. Details of the studied lakes and their catchments

	Kalliojärvi	Kallio-Kourujärvi	Kantele	Kuninkaisenlampi	Linnanlampi
Location	63°14'N, 25°22'E	62°33'N, 27°00'E	63°29'N, 26°39'E	62°58'N, 28°14'E	63°19'N, 27°10'E
Surface area (km^2)	0.15	0.13	0.10	0.05	0.05
Drainage area (km^2)	9.7	10	28	1.1	11
Catchment	6.3	1.5	1.0	1.0	9.0
Maximum water depth (m)	12.3	11.0	12.0	10.1	11.0
Elevation (m a.s.l.)	121	117	108	82	96
Catchment composition	moraine, gravel, peat formations bedrock outcrops,	sand moraine, sand formations, peat formations, bedrock outcrops	fine grained moraine, clay, peat formations, bedrock outcrops	fine grained moraine, silt, clay, peat formations, bedrock outcrops	fine grained moraine, clay, peat formations, bedrock outcrops

2.1.3 Lake Kuninkaisenlampi

Lake Kuninkaisenlampi (Figure 2) is located at an altitude of 82 m a.s.l. in the municipality of Juankoski (62°58'N, 28°14'E) and is part of the Nilsiä water course. At present, the majority of the lake is surrounded by agricultural fields, pine forests and meadows. The catchment is composed mainly of Quaternary, nutrient rich, fine-grained tills, silt deposits and some bedrock outcrops (Maankamara, DigiKP). The bedrock is composed of gneiss and tonalite (Bedrock of Finland, DigiKP).

The trophic state of Lake Kuninkaisenlampi is hyper trophic with a total phosphorus level of 120 µg/l and nitrogen 1100 µg/l (HERTTA database). Lake Kuninkaisenlampi is an elongated lake with a maximum depth of 10.10 m, a surface area of 0.07km^2, and a drainage area of 1.1 km^2. Lake Kuninkaisenlampi has an inlet, which enters from the southeast and one outlet to the northwest where the lake has a connection to Lake Muuruvesi, which is on the same level.

2.1.4 Lake Kantele

Lake Kantele (Figure 2) is located at an altitude of 108 m a.s.l. in the municipality of Kiuruvesi (63°29'N, 26°39'E). The lake is currently surrounded by agricultural fields, forest management areas, meadows, and a small private natural conservation area. The catchment is composed mostly of fine-grained tills and bedrock outcrops with minor occurrence of silt and peat deposits (Maankamara, DigiKP). The bedrock is composed mainly of granitoids and some paragneisses and dioritoids (Bedrock of Finland, DigiKP).

Lake Kantele is hypertrophic elongated lake with maximum depth of 12.4 m, a surface area of 0.1 km^2 and a drainage of 28km^2, while the catchment is approximately 1 km^2. There are three inlets to the lake, one at the northern end, and two on the western side of the lake. The single outlet is located at the eastern side of the lake.

2.1.5 Lake Linnanlampi

Lake Linnanlampi (Figure 2) is located at an altitude of 96 m a.s.l. in the municipality of Maaninka (63°19'N, 27°10'E) and is part of the Iisalmi watercourse. The lake is surrounded by meadows, a forest management area and agricultural fields, however, there is currently very little human residency on the lake catchment. The catchment is composed mainly of fine-grained tills, but there are some clay and carex peat deposits and bedrock outcrops in the catchment (Maankamara, DigiKP). The bedrock is composed of granitoids, paragneisses and diorites (Bedrock of Finland, DigiKP).

Lake Linnanlampi is a eutrophic and dimictic lake (HERTTA database), which has an oval shaped basin with a maximum water depth of 11 m, a surface area of 0.05km^2 and a drainage area of 11 km^2, of which the immediate catchment is 9 km^2. There are two inlets to the lake, a natural one drains into the lake from the north, and an artificial inlet drains into the lake from the southern bog area. An outlet on the eastern side ultimately drains into Lake Onkivesi.

2.2 Climate of the study region

The study region is in the southern boreal vegetation zone, where the coniferous forests are dominated by pine and spruce (Ruuhijärvi, 1988), in between the large continental Siberian land masses and the Atlantic Ocean. Thus, the region experiences climatic characteristics of both continental and maritime climate (Cohen et al., 2001; Meeker and Meyewski, 2002; Garcia-Herrera and Barriobedro, 2006; Hurrell and Deser, 2009). The Baltic Sea further increases the marine climatic effects on the western corner of the study region. The northern location explains the great contrasts between seasonal temperatures (Figure 3), although the contrast is balanced by the Atlantic Ocean and particularly the Gulf Stream, compared to more continental locations. The longest instrumental records of daily temperature variation and monthly precipitation are available from AD 1890 for Jyväskylä (Lake Kalliojärvi and Kallio-Kourujärvi) and Kuopio (Lake Kantele, Lake Kuninkaisenlampi and Lake Linnanlampi). The 30-year mean annual temperature (1961-1990) is 3.2°C in Jyväskylä and 2.9°C in Kuopio, however, the difference is larger at the coldest and warmest seasons with a January (coldest month) means of -9.3°C and -10.3°C and a July (warmest month) means of 16.1°C and 16.6°C, in Jyväskylä and Kuopio respectively (NORDKLIM, 2002). The annual precipitation is slightly higher in Jyväskylä (692 mm) than in Kuopio (644 mm) of which about one third to half precipitates as of snow. A stable snow cover usually develops before the end of November, and melts at the end of April (Solantie, 1987). Lake surfaces freeze in central and eastern Finland area around October-November, about the same time as the snow cover develops, but thaws a little later than the melting of the snow cover, usually in mid-May (Kuusisto, 1986).

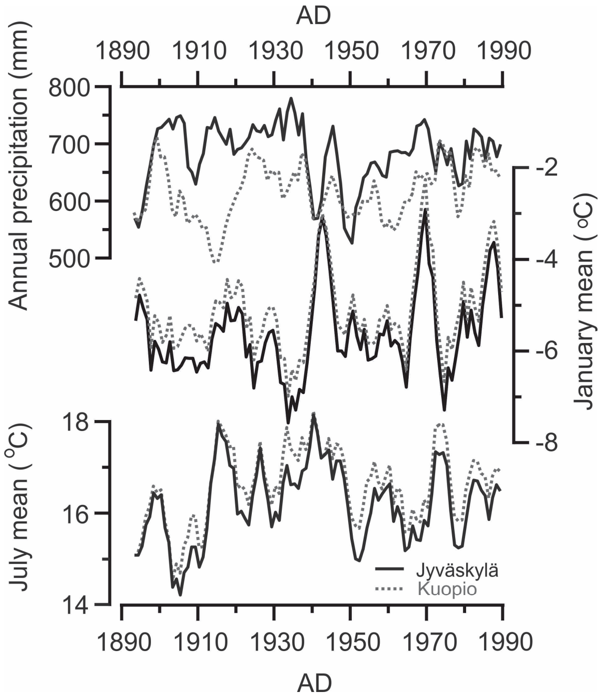

Figure 3. Recorded annual precipitation, January and July temperature variability from Jyväskylä (black solid line) and Kuopio (grey dashed line) meteorological stations, with a 5-year moving average (NORDKLIM, 2002). Temperature and precipitation calculations are given in chapter 3.12.

The duration of the ice cover varies being shortest at the sites of Linnanlampi and Kuninkaisenlampi (132-203 days) and longest at the Kalliojärvi site (150-206 days) (HERTTA database). Snow pack water equivalent values vary from 41-199 mm (Kalliojärvi site) to 85-262 mm (Kuninkaisenlampi site) (HERTTA database). The highest river discharges were measured in May at each study site. The duration of the spring flood event i.e. a number of days when the river discharge exceeds the spring mean (Paper I, III), varies greatly from a few days to nearly three months at every site (HERTTA database). The variation in flood event duration is the smallest at the Kantele site (9-68 days) and highest at the Kalliojärvi site (15-91 days). In general, the shortest flood events occurred at the Kuninkaisenlampi site (median 44 days) and longest at the Kalliojärvi site (median 60 days) (HERTTA database).

2.3 Sediment types

Lake sedimentation follows the cyclic change of seasons. Variable conditions lead to differences in sedimentary material, which may be preserved on the lake floor in favorable conditions. The appearance of varves and the characteristics of laminae within the varve type depends on the sedimentary environment. Two types of annually laminated sediments were used in this thesis, clastic-biogenic varves that are common in boreal lake environments and biogenic varves. In both cases, the varve year differs from the calendar year as the varve year begins in spring at the onset of either spring floods (clastic-biogenic varves) or diatom blooms (biogenic varves). Clastic-biogenic varves consist of three laminae (Figure 4). A varve year begins with a minerogenic lamina (i) that is composed of lithic clasts, mostly quartz and feldspar. The mineral matter is eroded and transported from the catchment during spring, when the melting snow causes floods. The second lamina (ii) consists of biogenic matter from allochthonous and autochthonous sources. It is transported from the catchment by the streams and wind and produced in the lake during the growing season; it contains remains such as macro and microfossils, plant remnants, algae and well degraded amorphous organic matter. Generally, the boundary between the first and second laminae is quite clear. The third lamina (iii) consists of humic substances and very fine-grained highly degraded, homogenous organic matter, which is accumulated during quiet waters in the course of the winter ice cover. Since the second lamina grades into the third lamina type, their boundary is not very clear in contrast to the boundary between the third and first laminae, which is very distinct (Figure 5).

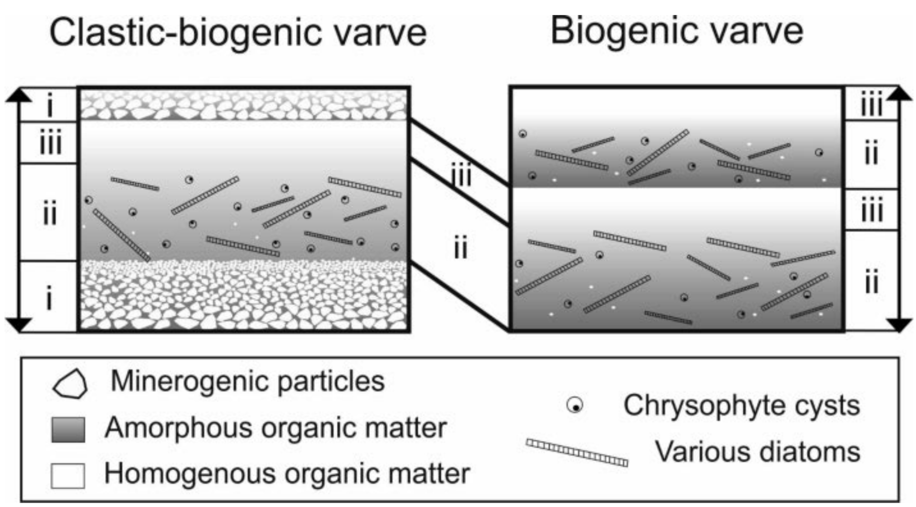

Figure 4. Schematic illustration showing the principal constituents and the structure of the clastic-biogenic (Paper I, III, IV) and biogenic varves (Paper II).

Biogenic varves in Finland, on the other hand, consist of similar second and third laminae to the clastic-biogenic varves, but lack the minerogenic laminae (Figure 4, 5).

However, a varve year begins almost in accordance with that of the clastic-biogenic varve year as a consequence of spring diatom blooms. The lack of minerogenic laminae is explained by the catchment characteristics. The bog areas around the lake, as well as the lack of fine-grained erodible minerogenic matter such as clays and silts in the catchment, can explain the missing minerogenic lamina. Additionally, thickly forested catchments may further decrease erosion.

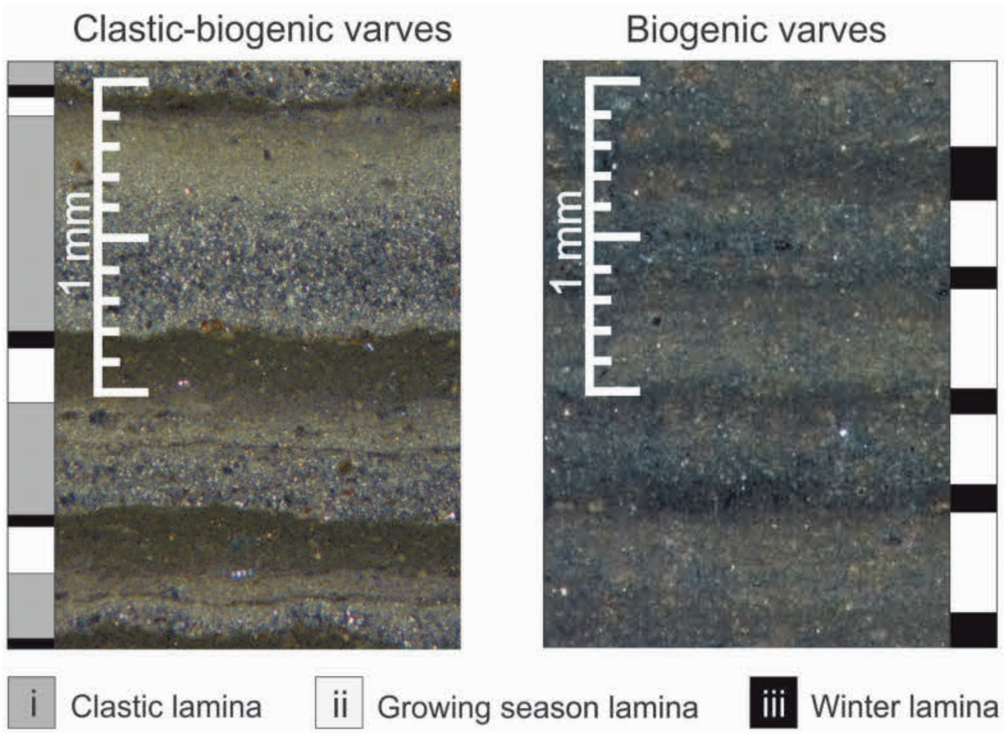

Figure 5. Microscopic image from thin sections under dark field illumination and 6x magnification showing the clastic-biogenic varves from Lake Kalliojärvi (left; Paper III) and biogenic varves from Lake Kallio-Kourujärvi (right; Paper II).

3. MATERIAL AND METHODS

3.1 Search for undiscovered varved lake sediments

Between 2008 and 2010, the search for undiscovered lakes with annually laminated sediments was carried out in order to increase the number of spatial distribution of varved proxy records in Finland. Such systematic surveys have been conducted widely at the turn of 21st century, for example, in Canada (Larsen and MacDonald, 1993; Larsen et al., 1998), Finland (Ojala et al., 2000), Sweden (Zillen et al., 2003), and in northern Poland (Tylmann et al., 2013). The initial search was done with maps where certain bathymetric and geological boundary conditions were evaluated. These included catchment and basin characteristics that favor the varve formation (Ojala et al., 2000), which are as follows: 1) the anoxic conditions on the lake floor that are a prerequisite for varve structure and organic matter preservation; lakes with a water depth of 10 meters or more, were chosen 2) the accumulation of fine grained material is crucial for clastic-organic varve formation. Agricultural fields on the lake catchment suggest the presence of fine-grained minerogenic matter. The minerogenic particles are transported from the catchment into the lake via inlets, and at least one inlet is considered to be a prerequisite to ensure adequate sediment transport. 3) the hills surrounding the lake protect the lake from wind and wave activities and possibly restrict erosion on the lake bottom and thus decrease resuspension and resedimentation. 4) a basin morphometry is critical. If the lake basin is very steep or the area of the deepest part is small, the risk of slumps in the sediment record increase. Thus, lake basins with a wide deep area are favored. About 70 promising lakes were chosen for examination with sediment coring. The selected lakes were test cored during the winter with a Russian type of peat corer (Figure 6).

Figure 6. Freshly cored varved sediments from Lake Kalliojärvi from the blade of the Russian peat corer. Photo by Timo Saarinen

The sediment sample on the peat corer blade was carefully studied with a glass blade and water to evaluate the presence and quality of varves. If varved structures were observed in the sedimentary sequence, the water-sediment interface was carefully cored in order to assure the varve formation until present day. A few more corer samples were obtained from different depths in potential sequences in order to evaluate the quality of varve structures and investigate how deep the varve structures extended.

Altogether, 70 promising lakes were cored from central and eastern Finland, of which 36 lakes were at least partially laminated and 23 with more extensive and continuous records of laminated sequences that were potentially varves (Table 2). Promising, potentially high quality varves were found in 13 lakes from which four lakes were chosen for this doctoral thesis due to their location and extremely clear varve records. The annually laminated nature of four of these lakes was investigated and confirmed (Paper I-IV).

3.2 Coring

The Lake Kallio-Kourujärvi, Kalliojärvi, Kantele, Kuninkaisenlampi, and Linnanlampi were cored from the ice during the winters of 2008-2010. The cores were obtained from the deepest part of the lake basins from each study site for the varve studies and paleomagnetic measurements (Table 3). A rod operated piston corer and PVC core tubes with length of 250-500 cm and an inner diameter of 6.4 cm were used. Several parallel cores were obtained, a few meters apart, from each lake. When working on the ice and during transportation, care was taken not to allow any freezing of the cores. The sediment cores were stored in a cold room at a temperature of 5°C. Coring was generally successful, although the loss of the water-saturated topmost sediment could not be prevented. The loss of high water containing and loose uppermost sediment varied between 1 and 14 cm.

Table 2. The potential and proven varved lake sediments found during the project. The lakes with high varve potential and quality for further studies are marked with an asterisk, cb = clastic-biogenic type, b = biogenic type

	Lake	Municipality	Surface area (km^2)	Maximum water depth	Lamina type	Length of laminated sequence
1	Alvajärvi	Jyväskylä	2.12	14.9 m	cb	> 1.0 m
2	Hiidenjärvi	Tuusniemi	0.11	15.7 m	cb	?
3	Honkajärvi	Tuusniemi	0.13	11.10 m	cb	?
4	Kalliojärvi*	Viitasaari	0.15	12.4 m	cb	> 3.3 m
5	Kantele*	Kiuruvesi	0.10	12.4 m	cb	> 2.5 m
6	Kuninkaisenlampi*	Juankoski	0.05	10.25 m	cb	> 2.0 m
7	Leväjärvi*	Suonenjoki	0.43	19.9 m	cb	~ 2.0 m
8	Lempinen*	Kaavi	0.16	20.61 m	cb	> 1.5 m
9	Linnanlampi*	Maaninka	0.05	10.44 m	cb	> 1.7 m
10	Luikujärvi	Juva	1.55	18.88 m	b	?
11	Mätäsjärvi	Lapinlahti	0.56	14.0 m	cb	?
12	Palojärvi*	Kiuruvesi	0.27	13.34 m	cb	> 3.2 m
13	Pieni Humalajärvi*	Jyväskylä	0.26	11.5 m	cb	> 2.8 m
14	Pieni Joutenjärvi*	Tuusniemi	0.04	13.25 m	b	> 2.0 m
15	Pitkäjärvi	Mikkeli	1.44	20.75 m	b	?
16	Pitkälampi*	Tohmajärvi	0.25	18.5 m	cb	?
17	Riihijärvi*	Leppävirta	0.53	19.49 m	cb	> 1.2 m
18	Rukkojärvi*	Polvijärvi	0.83	20.6 m	cb	> 2.6 m
19	Sikolampi*	Mikkeli	0.25	15.11 m	b	> 1.5 m
20	Suurijärvi	Leppävirta	1.17	16.1 m	cb	> 3.0 m
21	Suuri Honkajärvi	Tuusniemi	0.08	11.05 m	b	> 1.0 m
22	Suuri Joutenjärvi	Tuusniemi	0.27	15.5 m	b	> 0.7 m
23	Suuri Susijärvi	Tuusniemi	0.44	22.60 m	b	> 1.0 m

3.3 Surface sediment samples

Surface sediment samples were obtained using a Limnos gravity corer (Kansanen et al., 1991). A Limnos gravity corer is ideal for sampling water and sediment interfaces with a loose topmost sediment which has a low compaction and a high water content. A mini freeze core sampling technique (Saarinen and Wenho 2005) was used to collect surface samples from the limnos gravity corer. An approximately 25 cm long hollow wedge shaped aluminum tube was pushed into the sediment in the Limnos sampler in a slow and constant manner. Crushed dry ice was poured into the sampler. Surface sediments froze around the mini freeze corer in 20 minutes. Several mini freeze corer samples were collected from each location in order to study the topmost varves (Table 3.). To protect the mini freeze corer from melting, they were transported in a cool box filled with dry ice and kept outside in the winter temperatures until stored in a freezer at a temperature of -18°C. Mini freeze corers were used to measure the loss of surface sediments in the piston corer samples and to bind the varve chronology comprised from the piston corer to the present.

Table 3. Sediment cores obtained from the Lakes Kallio-Kourujärvi (KKJ), Kalliojärvi (KAL), Kuninkaisenlampi (KUN), Kantele (KNT) and Linnanlampi (LIN) that were chosen for this study. Description of investigation: VA varve analysis XRF =µ-XRF analysis, CN = C/N ratio, PSV = paleomagnetic secular variation, FC = freeze corer

Analysis conducted	Lake	Core ID	Coring tool	Core length (cm)	Water depth (m)	Coring date
CN	KKJ	1A	Piston corer	228	11.02	3/2008
VA	KKJ	2A	Piston corer	205	11.02	3/2008
VA	KKJ	a, b	Limnos + FC	30	11.02	3/2008
PSV	KKJ	3A	Piston corer	291	10.90	3/2010
VA	KKJ	c,d	Limnos + FC	30	10.90	3/2010
VA,XRF	KAL	1A	Piston corer	232	12.30	3/2008
VA	KAL	a, b	Limnos + FC	25	12.30	3/2008
PSV	KAL	3	Piston corer	199	12.26	3/2012
VA,XRF	KUN	1	Piston corer	283	10.10	3/2009
PSV	KUN	2	Piston corer	238	10.10	3/2009
VA	KUN	a, d	Limnos + FC	30-35	10.10	3/2009
VA	KNT	2A	Piston corer	230	12.40	3/2009
VA	KNT	a, b	Limnos + FC	25	12.40	3/2009
VA	LIN	2A	Piston corer	160	10.54	3/2009
VA	LIN	a, b	Limnos + FC	25	10.54	3/2009

3.4 Sediment treatments

The sediment cores were opened in the laboratory using a circular saw and a knife. The core was split in half lengthwise using a wire. The exposed sediment surface was cleaned with a glass blade. Alternatively, with very organic sediments that are difficult to split without significant disturbance, only a slice of the plastic core was carefully removed revealing the sediment in the core. The cleaned sediment surface was covered with thin plastic film to protect the sediment from drying and contamination.

Sub-samples were taken continuously from the cores using aluminum molds (11.0 x 1.5 x 0.8 cm) with 1.5 cm overlap in a manner described by Haltia-Hovi et al. (2007). Sub-samples were dried using a water-acetone exchange method (Lamoureux, 1994; Tiljander et al., 2002). The water content of the sediment was measured enthalpimetrically, and the sediment was considered to be sufficiently dehydrated when the water content was less than 0.5% (Moran et al., 1989). Dehydrated sub-samples were impregnated in Spurr low-viscosity epoxy resin (Lamoureux, 1994; Tiljander et al., 2002) with component weight proportions of 130 parts of nonenyl succinic anhydride (NSA), 50 parts of epoxide resin (ERL 4221), 20 parts of diglycidyl ether of polypropylene glycol (DER 736) and 1 part of dimethylaminoethanol (DMAE). A small amount of acetone was added in the first two epoxy baths in order to improve impregnation (Pike and Kemp, 1996). A total number of 6-10 baths were applied at approximately 12-hour intervals. The samples were cured at 60°C for 48 hours. Epoxy impregnation preserves the varve structure and thus enables thin section and sample preparation, and better transportation and filing of the study material.

Epoxy impregnated sub-samples were separated from each other with a circular saw and the surfaces were polished using surface-grinding machine. Sample slabs were cut off from each sub-sample and they were levelled to the standard thickness of 1.8 mm for radiographs. Micro x-ray fluorescence (μ-XRF) analyses were carried out using the remaining material from the sub-samples. Thin sections (1.5 x 11 cm, thickness ca 20 μm) were made from the rest of the epoxy blocks following the technique of Lotter and Lemcke (1999) at Helmholtz Centre Potsdam (Lake Kallio-kourujärvi, Kalliojärvi and Kuninkaisenlampi) and in the University of Turku (1.5 x 11 cm, thickness approximately 130 μm; Kantele and Linnanlampi).

3.5 Low field magnetic susceptibility

Low field magnetic susceptibility (κ_{LF}, SI) was measured in order to correlate parallel cores. Low field magnetic susceptibility was logged from the plastic film covered sediment surface directly after opening and splitting the long cores. A Bartington MS2 susceptibility meter coupled with an MS2E1 spot reader sensor was used with an automatic measuring track, 2.0 mm measuring interval and 10 seconds analysis time.

3.6 X-Radiography

The 1.8 mm thick sub-sample slabs from Lake Kalliojärvi and Kuninkaisenlampi were radiographed using Soredex Mamex medical X-ray equipment, originally designed for mammography. Four sub-sample slabs at a time were placed on Agfa Structurix DW/D7 films with a calibration wedge, made from thin glass slips. The calibration wedge was used in order to enable adjustment and equalization of the grey scale values between each film throughout the varve record. A focal distance of 500 mm and a focus size of 0.1 mm were applied with an electric current of 10 mA and a tube voltage of 20 kV to the radiographs. An exposure time of eight to ten seconds was used depending on the sediment material. The exposure time was selected after several tests for each lake. The films were developed manually and a scanner (CanoScan 9900F) with a resolution of 1000 dpi was used to digitize the radiographs.

3.7 Digital image analysis and varve counting

Digital image analysis is a rapid tool for collecting quantitative high-resolution data along a varve sequence and the method has been established by several studies concerning clastic-biogenic varves (Ojala, 2005; Saarinen and Petterson, 2002). Digital image analysis was used to count and record the varve and laminae thicknesses of the varves from Lake Kalliojärvi and Lake Kuninkaisenlampi. An analytical line of one pixel wide and grey scale value of 0 was drawn perpendicular to the varve structures. The varve boundaries were automatically defined at the lowest deflection points on the grey scale value curve (Ojala and Francus, 2002). However, manual revision of the automatic varve counts was required. A binocular microscope, the polished sample blocks and thin sections were used for revision. Each varve count was based on a single varve analysis, however, each of the varve sequences were counted three times using different analytical lines to produce the varve chronology with error estimates.

The counting error was estimated separately for each hundred of the varve intervals and the cumulative counting uncertainty was calculated.

Density variations were recorded as a variation in grey scale values (0-255). Dense material, such as minerogenic particles, absorbs x-rays which causes a shadow on the film that is observed as a lighter shade. Varve parameters were calculated from the relative grey scale data following the procedure used by Tiljander et al. (2002; 2003). As an output result, several physical varve parameters were obtained: light sum (LS) that is a sum of all grey scale values of each pixel of a varve, varve thickness, mean X-ray density, and minimum and maximum x-ray density value in each varve. The Dark Sum (DS) was calculated from the varve parameter data with the formula:

$$DS = 255 \times \text{number of pixels} - LS,$$

where 255 is the largest gray scale value representing pure white. The increased light sum is related to the increased accumulation of minerogenic particles while the increased dark sum denotes an increase in the accumulation of organic matter. Varve thickness (VT) was calculated with the formula:

$$VT = \text{number of pixels} \times 0.0254 \text{ mm},$$

where 0.0254 mm is the known length of a pixel resulting from 1000 dpi scanning.

3.8 Microfacies analysis

Microfacies analysis provides detailed information of the annual sediment cycle, such as the presence and location of the minerogenic particles, diatom blooms, and microscopic plant and insect remnants in the varve. For the organic varves with no clear minerogenic enrichments the microscopic analysis provides the principal method for counting the varves and measuring the thickness of a seasonal laminae. Microfacies analysis is also a practical tool when there is a significant change in sediment composition from a very low mineral content to a very high mineral content, which leads to failure in finding a functional exposure time in order to produce X-ray images. Due to these reasons, thin sections from Lake Kallio-Kourujärvi, Linnanlampi, Kuninkaisenlampi and Kantele were analyzed using a stereomicroscope (Nikon SMZ800), dark field illumination and 6 x magnification. In addition, thin sections from Lake Kuninkaisenlampi were analyzed using a Zeiss Axioplan microscope using 50 x magnifications with polarized light and alternately uncrossed or crossed polarizers (Weege, 2011). Varve analysis was performed along an analytical line drawn perpendicularly to the varve structures avoiding disturbed or poorly preserved parts and cracks in the sub-sample. The thickness of the growing season lamina (GSL), winter lamina (WL), clastic lamina (CL; absent in the case of Kallio-Kourujärvi organic varves), and total varve thicknesses were measured. An analysis resolution of 0.05 mm was achieved. Each of the hundred year-intervals were calculated three times in order to estimate the counting error and to calculate cumulative counting uncertainty.

3.9 Micro X-ray fluorescence

Micro x-ray fluorescence is a rapid, non-destructive and semi-quantitative tool to record element variation in the sediment, potentially even at sub-annual resolution (Rothwell and Rack, 2006). During the analysis, sediment is excited by x-radiation that causes ejection of electrons from the inner atomic shells. As a result, electrons from the outer shells fall back into the inner shells to fill the vacancies. The energy difference between inner and outer shells causes surplus energy that is emitted as x-radiation, which is then detected by a detector. Each element has a characteristic energy emission and wavelength spectrum that allows recognition and estimation of the relative element abundance in the sample (Rothwell and Rack, 2006).

Major element analyses were performed on Lake Kalliojärvi and Lake Kuninkaisenlampi impregnated sediment blocks. The analytical lines were determined for each sub-sample at the most representative parts to avoid deformed varve structures and cracks. The line scans of the sub-samples were performed using a vacuum-operated Eagle III XL µ-XRF spectrometer. A rhodium x-ray tube was used at a tube voltage of 40 kV and a tube current of 350 µA. Element scanning was performed with a spot size of 120 µm, a step size of 100 µm and a counting time of 50 seconds. Element intensities of aluminum (Al), calcium (Ca), chlorine (Cl), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), silica (Si), and titanium (Ti) are expressed as counts per seconds (cps). Chlorine is the only element component in epoxy resin that is detectable using µ-XRF (analytical range with the used configuration is from Na to U) and increased counts of Cl with the images of the analytical line was used to determine the cracks in the sediment and delete crack counts from the µ-XRF data.

3.10 Paleomagnetism

Paleomagnetic secular variation (PSV) is recorded in sediments as a variation in remanent magnetization (NRM). Major secular variation features in inclination and declination (Snowball et al., 2007; Turner and Thompson, 1981) are widely used for dating sediments. PSV was measured for an independent age control of the varve chronology. Sub-samples for paleomagnetic measurements were taken from a freshly opened core, instantly after logging the low field magnetic susceptibility. A sample interval of 3.0 cm was applied for all the cores and plastic boxes with a volume of 6.9 cm^3 were used. The boxes were stored in moist conditions on a tray sealed with plastic film in a cold room at 5 °C until the measurements were carried out, which was within a week of opening the core.

Natural remanent magnetization (NRM) was measured using a Molspin portable Minispin spinner magnetometer in the Geology division at the University of Turku, using 6 sample box positions. The cores were orientated for the z-axis only and as a result, declination data are relative.

3.11 C/N analysis

The organic matter in the lake is derived either from autochthonous or allochthonous sources. The source can be evaluated using a C/N ratio, because algae typically have lower C/N ratios than vascular cellulose-rich terrestrial plants (Meyers and Ishiwatari, 1993; Meyers and Lallier-vergés, 1999). Plankton and bacteria usually have a C/N ratio of 5-8 (Meyers, 1994), peat bogs about 17 (Ertel and Hedges, 1984), terrestrial plants have ratios from 20 to 100 (Meyers and Lallier-vergés, 1999). A C/N ratio yields information concerning the source of the organic matter. A higher C/N ratio reflects an increased input of terrigenous organic matter.

Every third sample box used for paleomagnetic measurements from Lake Kallio-Kourujärvi, were thereafter used for C/N analysis resulting in a 9 cm sample interval. The sediment was air dried at room temperature in a drying cabinet for 24 hours and homogenized. The total carbon and nitrogen analyses were carried out using the ThermoFinnigan FlashEA 1112 NC Analyzer at Ambiotica Laboratory (University of Jyväskylä). The gas chromatography method is based on complete combustion of the sample in a high temperature (about 1800 °C) followed by the determination of the produced elemental gases due their characteristic retention time. The concentrations of

C and N are expressed as a percentage of the dry sediment mass, from which the C/N ratio is calculated.

3.12 Meteorological and hydrological data

Meteorological data were downloaded from the NORDKLIM database (Nordic meteorological services, NORDMET steering committee, 2002) in order to compare the physical varve properties with instrumental meteorological records. Monthly precipitation and temperature records have been available from Kuopio and Jyväskylä meteorological stations since AD 1890. Mean precipitation and temperatures were calculated from the monthly data from 1961-1990. Variation in winter precipitation and growing season precipitation were studied by calculating the precipitation sum of winter months (November-April) and the months of the growing season (May-September) of each year. The growing season temperature was also calculated from the monthly data.

Hydrological data were downloaded from HERTTA database (Finnish Environment Institute) in order to study the influence of local hydrology on sedimentation. Hydrological data included daily river discharge data, snow water equivalent measurements, ice formation and ice-out dates. Maximum river discharge (Q_{max}) dates and volumes were observed, the mean discharge of the melting season (April-June) were calculated from each location and the length of flood episodes (Q_{dur}) were calculated as the number of days with a discharge over the April-June mean. The duration of the ice cover (ICE_d) was calculated from the ice formation and ice out dates. Unfortunately, no hydrological data were available from the catchment of the studied lakes. For that reason, the closest point of data available was used, however, the distance from the lake to the hydrological data point varied from a few kilometers up to 20 km. Furthermore, the available hydrological data were temporally scattered and mostly available only since the 1960s.

3.13 Statistical and spectral analyses

Correlations between varve parameters and meteorological data from two meteorological stations were determined for a 100-year period in order to evaluate the varve sensitivity for climatic variables. Total varve thickness (VT), biogenic lamina thickness (BL) from Lake Kallio-Kourujärvi record and clastic lamina thicknesses (CL) from Lake Kalliojärvi, Kuninkaisenlampi, and Linnanlampi were compared with the total annual precipitation (R_{ann}), the winter precipitation (R_w), the growing season precipitation (Rgs), the winter mean temperature (T_w), the growing season mean temperature (T_{gr}), the number of snow cover days (SC, snow cover more than 50%), the length of ice cover period (ICE_d), the snow water equivalent in April (SWE_a), the maximum river discharge (Q_{max}), and the duration of flood episodes (Q_{dur}).

An R 2.14.1 program (R Development Core Team, 2011) was used for the statistical analyses. Correlation analyses were performed for all possible time intervals on combinations between dependent (VT, BL, CL) and independent (R_{ann}, R_{gs}, R_w, T_{gs}, T_w, T_{may} SC, Q_{max}, Q_{dur}, Q_{amj}, ICE_d, SWE_a). A Kolmogorov-Smirnov normality test was used to test the normal distribution of the samples if the sample size was more than 50 years. A Shapiro-Wilk test was applied to smaller sample sizes. In the case of normally distributed variables, Pearson's correlation analyses were performed. If at least one of the variables was not normally distributed, then Spearman's correlation analysis was used instead. Statistically significant ($p < 0.05$) correlations with i) the highest absolute values for periods longer than 10 years and ii) the longest periods with correlation more than 0.5, were observed from the data.

In order to identify the cycles in the varve records and solar activity (TSI proxy record), the classical frequency analysis was applied, using the dplR program library (Bunn, 2008). The red-noise corrected spectrum of the time series was computed and the significance of spectral peaks was tested using a Chi-squared distribution. The common spectral properties were studied in order to study the phase relationship between the time series. For this study, cross-wavelet analysis (Grinsted et al., 2004) was applied. Annually resolved varve time series were linearly interpolated to the sampling resolution i.e. a 5 year resolution for TSI data (Steinhilber et al., 2012) and a 10 year resolution for $\Delta^{14}C$ record (Reimer et al., 2013) before generating the wavelets.

4. RESULTS

4.1 Chronology and error estimations

Three long varve chronologies were reconstructed from the lakes in central and eastern Finland. In total 3000, 3607 and 4132 varves were counted from Lake Kallio-Kourujärvi (Paper II), Lake Kuninkaisenlampi (Paper IV) and Lake Kalliojärvi (Paper III), respectively. Cumulative counting errors were estimated as + 53 (+2.3%) and – 56 (-2.5%) varves for Kallio-Kourujärvi (Paper II) and +87 (+2.1%) and -91 (-2.2%) varves for Kalliojärvi (Paper III). Cumulative counting error for Lake Kuninkaisenlampi was estimated to be +30 (+0.8%) and -38 (-1.0%) varves when using an image analysis technique following the method of Lotter and Lemcke (1999), but ±94 (2.6%) varves when using two different methods: image analysis and micro facies analysis by two different analysts (Weege, 2011; Paper IV).

In addition, a 100 varves were counted from Lake Kantele, and Lake Linnanlampi. Cumulative counting errors were estimated to be ±0.3% and ±1.0% varves for Lake Kantele and Linnanlampi, respectively (Paper I).

Generally, the small cumulative error estimations denotes a uniform identification of the varves related to the high quality and preservation of the structures. However, varve quality is not constant throughout the sequence but varies between well and less well preserved sections. The best preserved 100-year intervals of varved sediment occur between 3750 and 3650 BP in Kalliojärvi, between 1650 and 1550 BP in Lake Kallio-Kourujärvi, between 3100 and 3000 BP and 2800 and 2600 BP in Lake Kuninkaisenlampi. These intervals were defined as the best varve quality due to the same number of varve counts each time. The poorest varve preservation was indicated in Lake Kalliojärvi between 250 and 150 BP, leading to a counting error of ±7.2%. Deviation in the number of varves in repeated counts is an artefact of unclear varve boundaries that can be the result of coring or sub-sampling, but also of natural causes. The lack of spring flood or an occurring flood event in the autumn could cause difficulties in positioning the varve boundaries correctly. Such problems are less frequent in micro facies analysis where the seasonal succession of sediment bands can be better distinguished. However, varves can be simply poorly preserved, for example, due to increased oxygen availability or lake water level changes.

Paleomagnetic measurements were used to provide independent age control for the varve dating of the three chronologies. The most prominent inclination (γ, δ, ε', ε) and relative declination (d, e, f) features (Turner and Thompson, 1981) are well dated from several varve records from Fennoscandia (Haltia-Hovi et al., 2010a; Snowball et al., 1999, 2007) and can be used for dating. The three varve records in this thesis were compared with the North Karelian Stack (Paper IV) constructed from two varved lake records in eastern Finland (Haltia-Hovi et al., 2010a), Nautajärvi PSV (Paper II) constructed by Ojala and Alenius (2005), and Fennostack (Paper III) that was compiled from several Swedish and Finnish lake records (Snowball et al., 2007). The relatively small age deviations in major secular variation features between the North Karelian Stack and our data provides further support for the varve dating (Figure 7).

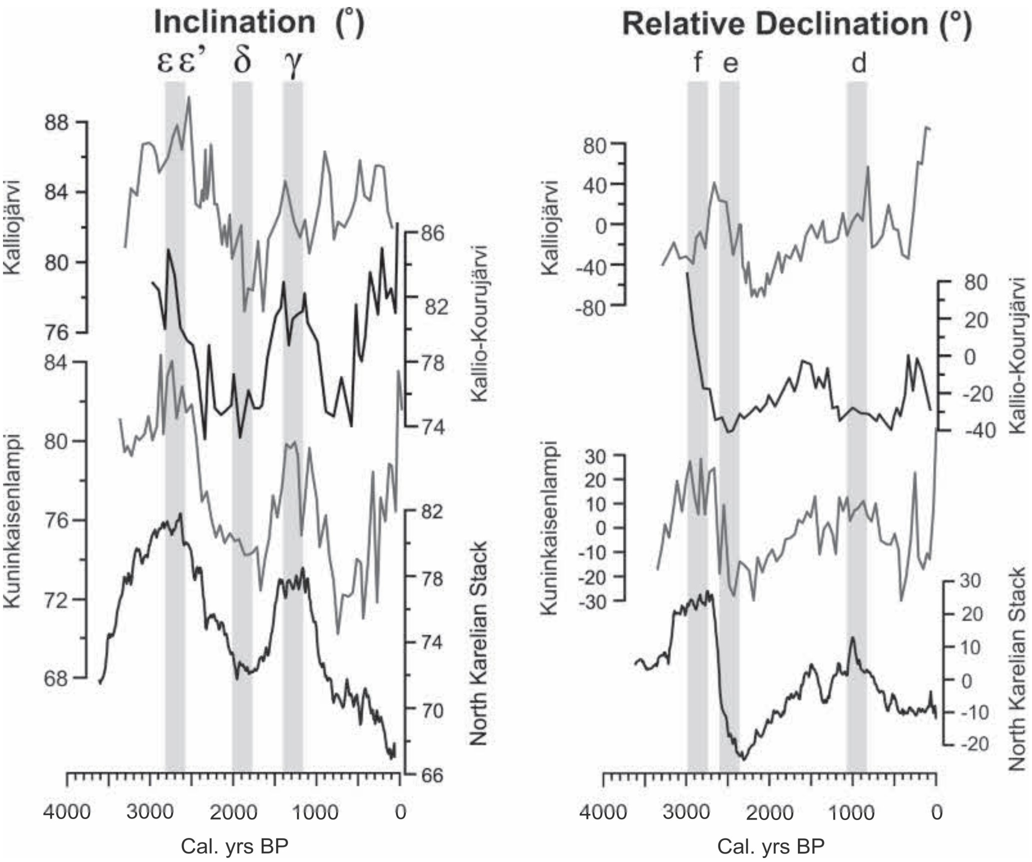

Figure 7. Inclination and relative declination from Lakes Kalliojärvi, Kallio-Kourujärvi and Kuninkaisenlampi compared with the North Karelian Fennostack (Haltia-Hovi et al., 2010a)

4.2 Characteristics of the sediment records

The sediments of Lake Kalliojärvi, Lake Kallio-Kourujärvi and Lake Kuninkaisenlampi have been continuously varved since 3000-4000 BP to the present. The total varve thickness and clastic lamina and biogenic lamina thicknesses were measured separately. These proxies show strong variations prior to ca 2500-3000 years BP and during recent times (Paper II, III, IV). The chemical composition determined from Lake Kuninkaisenlampi (Weege, 2011; Paper IV) and Lake Kalliojärvi sediments (Paper III) shows large variations through time. The elements were divided into two geochemical associations according to their occurrence.

Silica and titanium are common constituents of silicate minerals in plutonic rocks and thus these elements as well as Al, Ca, K, Mg largely compose the minerogenic clasts and the minerogenic laminae (Figure 8). This group of elements constitutes detrital silicate mineral association. Iron and manganese comprise a re dox sensitive association which reaches maximum values in organic laminae (Figure 8).

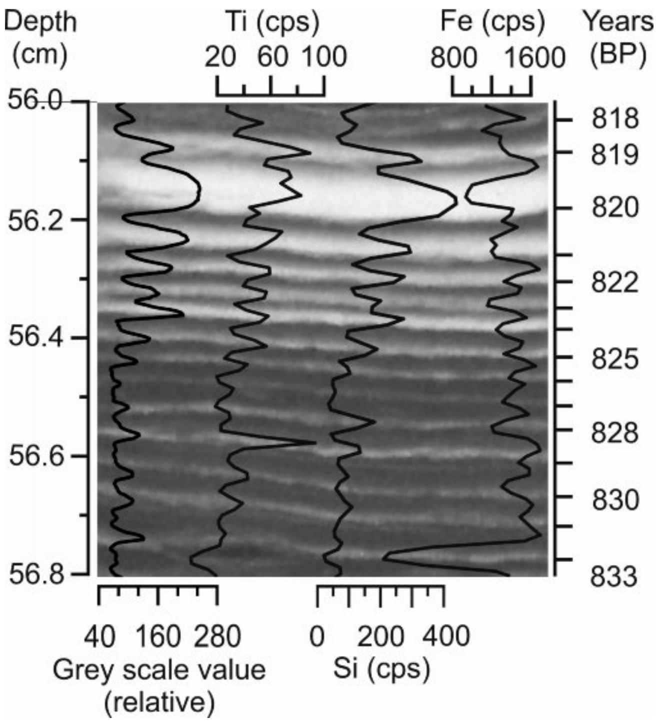

Figure 8. The grey scale value variation, and chemical elements analyzed with μ-XRF from Kalliojärvi plotted on the x-ray image. The grey scale value, titanium (Ti), and silica (Si), expressed as counts per second (cps), show the highest peaks on the minerogenic laminae (bright) and the lowest on organic lamina (dark), while iron (Fe) is enriched in the organic laminae.

All of the investigated varve sequences experienced increasing varve thicknesses during the most recent 20 years (1990-2010 AD; Paper II, III, IV). Increased varve thickness of the topmost sediments is caused by low compaction and high water content. A significant increase in catchment erosion reflected by an enhanced clast accumulation was indicated in Lake Kalliojärvi in the 1960's (Paper III), in Kuninkaisenlampi in the 1920's (Paper I, IV) and in Lake Linnanlampi at AD 1906 (Paper I). In the biogenic varve record of Lake Kallio-Kourujärvi, some minerogenic matter, however, has been deposited occasionally since AD 1890 (Paper II). The sedimentation rate of organic matter has been enhanced since AD 1550 in Lake Kuninkaisenlampi (Paper IV), AD 1600 AD in Lake Kallio-Kourujärvi (Paper II), but only since AD 1850 in Lake Kalliojärvi (Paper III).

4.3 Review of papers I-IV

4.3.1 Paper I: Saarni, S., Lensu, A., Haltia, E., Saarinen, T. Winter climate signal in boreal clastic-biogenic varves; a comprehensive analysis of multiple varved records from 1890 to 1990 AD and instrumental data from eastern Finland.

This paper presents three recent clastic-biogenic varved lake records spanning the years AD 1890 to 1990 from the region characterized by fine-grained tills in eastern Finland. The annual variability of the minerogenic matter accumulation was compared to meteorological records and hydrological observations monitored in the vicinity of each lake. The meteorological variables used were a mean spring (April-June) river discharge (Qamj) and a maximum spring river discharge (Qmax), snow pack water equivalent of the April (SWE), duration of ice- (ICEd) and snow cover (SNWd), a mean May temperature (Tmay), May precipitation (Rmay) and winter (November-April) precipitation (Rwin). The statistical correlations reveal that the maximum river discharge generally controls the clastic matter supply from the lake catchment; the larger the discharge, the more minerogenic matter deposited. However, the studied lakes showed consistently enhanced minerogenic matter accumulation during decreased winter precipitation and snow accumulation, which contradicts earlier studies of clastic-biogenic varve records from central Finland, where increased clastic input is related to enhanced snow accumulation. Increased snow accumulation has been related to increased spring flood events that enhance catchment erosion. The catchment geology can explain the significant difference between the earlier studied lakes and the three lakes of this study. Fine-grained tills are very sensitive to frost formation. Frost that develops deeper during winters of low snow accumulation, prevents melt waters from infiltrating into soil during spring floods. This would increase catchment erosion through enhanced surface run-off. Furthermore, deeper soil freeze-thaw cycles could reduce soil stability. The results show that the region of fine-grained tills is sensitive to variation in the snow accumulation in a way that increased erosion is related to low snow accumulation. However, even with very similar lakes and their catchments, the lakes can respond differently to the climate due to reasons that are not yet understood. The results highlight the importance of catchment characteristics to lake sensitivity to record climate variables. However, anthropogenic activities in the drainage area may have superimposed the natural signal in varve records.

*4.3.2 Paper II**:** Saarni, S., Saarinen, T., Lensu, A., 2015. Organic lacustrine sediment varves as indicators of past precipitation changes: a 3,000-year climate record from Central Finland. Journal of Paleolimnology 53: 401-413.*

The article presents an organic varve record from Lake Kallio-Kourujärvi, which covers the last 3 000 years. The sediment sequence was impregnated with low-viscosity epoxy resin and thin sections were prepared. Varve boundaries were analyzed using a binocular microscope and dark field illumination. Microfacies analyses revealed the varve thickness variation for the last 3000 years. The varve thickness variation from 1890-1990 AD was compared with the meteorological data from Jyväskylä meteorological station. The correlations between varve thickness variation and growing season temperature and varve thickness variation and total precipitation were studied using statistical methods. A positive correlation between total organic matter accumulation and annual precipitation and growing season precipitation was observed. This suggests that increased precipitation enhanced the nutrient inflow into the lake. In this oligotrophic lake, nutrient availability is crucial for autochthonous production, but as a result of precipitation, an increased amount of allochthonous organic matter has been transported into lake as well. No explicit correlation was found between the growing season temperature and varve thickness. This suggests that organic varve thicknesses in oligotrophic lakes cannot be used as a proxy for past temperatures. However, Lake Kallio-Kourujärvi record can be used to study past precipitation changes in the Central Finland area. This is valuable since precipitation reconstructions are scarce in Central Finland, although information on the temporal and spatial variability of precipitation is important to better understand the changes in atmospheric circulation patterns.

4.3.3 Paper III: Saarni, S., Saarinen, T., Dulski, P., 2016. Between the North Atlantic Oscillation and the Siberian high: A 4000-year snow accumulation history inferred from varved lake sediments in Finland. The Holocene 26: 423–431

Winter climate variability can be studied using clastic-biogenic varve records. Clastic laminae are formed because of the erosional events in the lake catchment caused by spring floods following the rapid melting of snow. Thus, seasonal variations in minerogenic matter influx and deposition can be considered to reflect changes in winter precipitation and snow accumulation. In this article, changes in the clastic-biogenic varve record were reconstructed from Lake Kalliojärvi in Central Finland. The 2.30 m long varve sequence extends from the present to the last 4132 ± 91 years BP. The minerogenic matter accumulation was studied using digital image analysis of x-radiographs. Further information was achieved with major element determination carried out using μ-XRF. The minerogenic influx in Lake Kalliojärvi showed synchronous variations with the North Atlantic Oscillation (NAO) phases. Decreased snow accumulation occurred during the negative NAO phase. This suggests that during positive NAO phases, humidity brought by westerly airflows increases the snow accumulation in Central Finland, and thus Lake Kalliojärvi's record provides valuable information on the NAO variability since 3950 BP. In addition, past redox changes were investigated using the Fe/Mn ratio, which is increased during enhanced oxygen deficiency. The Fe/Mn record followed variations in the strength of the Siberian high pressure system. A strong Siberian high leads to cold winter and spring temperatures and a prolonged duration of the ice cover on the lake. Consequently, the winter stratification of the water column is prolonged which results in intensified oxygen deficiency on the lake floor.

4.3.4 Paper IV: Saarni, S., Muschitiello, M., Weege, S., Brauer, A., Saarinen, T. 2016. A Late Holocene record of solar-forced atmospheric blocking variability over Northern Europe inferred from varved lake sediments of Lake Kuninkaisenlampi. Quaternary Science Reviews 154:100–110.

The article presents a clastic-biogenic varve record from Lake Kuninkaisenlampi covering the last 3600 years. The 2.32 m long sediment core was impregnated in epoxy resin from which thin sections and x-ray images were obtained. Two methods by different analysts were used to construct the varve chronology and for comparison of the two techniques: (1) micro facies analysis from thin sections and (2) digital image analysis from x-radiographs from epoxy blocks. Major component elements were determined using μ-XRF. Comparison of varve data with the solar activity reconstructions revealed that increased catchment erosion occurs during low solar activity. The link between solar activity and catchment erosion was further studied using spectral analysis and recent hydrological data. The minerogenic matter accumulation exhibits multi-decadal to centennial-scale spectral coherency with solar activity. This was suggested to be caused by more frequent atmospheric winter blocking circulation induced by solar-forced changes in the stratosphere. The varve record revealed increased catchment erosion during shorter but more intense spring flooding events that are related to lower solar activity. Cold winters and decreased snow accumulation, on the other hand, were related to frequent atmospheric blocking which results in deeper ground frost. This leads to decreased water infiltration in the frozen ground during the spring and increased surface run-off leading to increased catchment erosion.

5. DISCUSSION

5.1 Evaluation of the fidelity of the long varve chronologies

The high varve quality of the investigated varve records provides continuous, precise, and accurate dating of sediment sequences which extend 3000 ± 56 years (Kallio-Kourujärvi; Paper II), 3 607 ± 94 years (Kuninkaisenlampi; Paper IV) and 4 132 ± 91 years (Kalliojärvi; Paper III) back in time. The varve dating was further supported by paleomagnetic measurements. The cores were directed only against the z-axis and declination features are very sensitive to any rotation of sediments cores. Sediment rotation during coring or while opening the core could very well explain why the declination feature d is not clearly recognized in Lake Kallio-Kourujärvi NRM record (Paper II). The small temporal lags between the dates of each lake record in comparison to North Karelian Stack (Lake Kuninkaisenlampi < 40 years, Lake Kalliojärvi < 150 years, Lake Kallio-Kourujärvi 200-300 years, Paper II; III; IV) are explained by different lock-in depths of natural remanent magnetization. The lock-in depth, the depth below which the magnetic particles are no longer re-aligned to the geomagnetic field but are locked into place by the non-magnetic sediment matrix after compaction and dewatering of the sediment (Hamano, 1980), can be significantly deeper in organic sediments leading to a lag of several hundred years (Mellström et al., 2015): this is very likely the case with the Lake Kallio-Kourujärvi sediments. The sedimentation rate in Kallio-Kourujärvi is significantly slower and the sediments are of relatively low density with a higher water content due to lack of minerogenic matter (paper II) compared to the clastic-biogenic sediments of Lake Lehmilampi (Haltia-Hovi et al., 2007, 2010a) and Kortejärvi (Haltia-Hovi et al., 2010a), from which the North Karelian Stack is compiled. In such sediments, a lock-in delay of 80-100 years is reported (Haltia-Hovi et al., 2010a; Saarinen, 1999). The smoothed Fennostack and North Karelian Stack could lead to small temporal deviations. Generally, simultaneous occurrence of PSV features in the studied lakes and North Karelian Stack supports the reliability of the constructed varve chronologies.

5.2 Anthropogenic influence on sedimentation

The continuous varve formation in Kalliojärvi, Kallio-Kourujärvi and Kuninkaisen-lampi reflects stabile depositional environments at 3000-4000 years BP. This is well in line with the general Holocene climatic and environmental development in Northern

Europe (Saarnisto 2000; Wanner et al., 2008; Hakulinen, 2009). The continuous varve formation indicates stable hypolimnetic conditions and absence of turbulence, currents, and slumping at the coring sites.

The recent increased minerogenic matter deposition reflects intensified anthropogenic land use in the lake catchments. Significantly increased catchment erosion begun AD 1960 at Lake Kalliojärvi (Paper III), AD 1920 at Lake Kuninkaisenlampi (Paper IV), AD 1906 at Lake Linnanlampi (Paper I), and AD 1890 at Lake Kallio-Kourujärvi (Paper II) suggest intensified human actions in the lake catchments. These changes are well in line with the meta-analysis results from large Europian dataset of varved sites that indicates spreading of hypolimnetic hypoxia since AD 1850 as a consequence of more intensively cultivated surface area (Jenny et al., 2016a; 2016b). In the record of Lake Kantele such a significant increase is not indicated (Paper I) which could mean that either intensified cultivation started at Lake Kantele earlier than in other sites, already beyond our 100-year sediment chronology or that the lake did not react to increased human actions as clearly. The slash-and-burn agriculture is suggested to have increased organic matter accumulation in the Lake Pieni-Kauro in eastern Finland (Luoto and Helama, 2010). In Lake Kallio-Kourujärvi and Lake Kuninkaisenlampi the increase in the sedimentation rate of organic matter coincides with the timing of the first human settlements in the area during the 16th century (Orrman, 1991; Soininen 1961) and could well reflect human activity. The difficult terrain of boulders, bedrock outcrops and steep slopes in the Lake Kalliojärvi catchment, could explain why this site remained unoccupied probably until modern times. The Lake Linnanlampi area very close to Lake Kuninkaisenlampi was occupied during the 16th century as well, but the varve record is too short in order to detect the signals of the early changes in organic matter caused by anthropogenic actions. Intensive land use began at the Lake Kallio-Kourujärvi, Lake Kuninkaisenlampi and Lake Linnanlampi sites in the 19th century when roads, and infrastructures were built on the area (Eskelinen, 1985) and slightly later at the Lake Kalliojärvi site, culminating in the 1960's in the construction of highway 775 (Grönroos, 2016), which intersects the lake catchment.

5.3 Organic matter accumulation as climatic record

The organic matter deposition on the lake floor is a sum of supply and degradation. The organic matter in the lake originates from allochthonous influx and autochthonous primary production (Meyers and Lallier-Vergés, 1999; Ojala et al., 2013). Allochthonous organic matter is transported from the lake catchment by river flow, wind and from the lake slopes by gravitation. Redeposited organic matter includes plant remnants such as shrubs and leaves, pollen, as well as dissolved humic substances. Autochthonous production depends on several factors such as light, water temperature and nutrient availability (Bradbury, 1988; Meyers and Ishiwatari, 1993). However, the net sedimentation rate of organic matter is not only dependent on the rate of primary production and influx, but also on the preservation and degradation of organic matter in the lake-catchments system. The degradation of organic matter already effectively starts in the water column due to microbial activities (den Heyer and Kalff, 1998; Meyers and Lallier-Vergés, 1999). Degradation is further continued on the sediment surface even when buried deeper by the microbial decomposers and macrobenthos (Hedges et a., 1999) and through organic carbon mineralization (Sobek et al., 2009; Gudasz et al., 2010). Postdepositional degradation processes are ultimately controlled by the chemical composition of the organic matter, sediment accumulation rates, and the oxygen concentration of the bottom waters (Meyers and Ishiwatari, 1993; Maerki et al., 2009).

Positive correlation between the biogenic matter accumulation and precipitation was observed from the organic matter records of Lake Kallio-Kourujärvi (Paper III) and Lake Kalliojärvi (Figure 9). Snow accumulation on the lake catchment is an important factor that controls the discharge during the spring flood event. This is reflected as a strong correlation between the maximum river discharge and snow water equivalent at the Kalliojärvi study site (r = 0.51) and Jyväskylä near the Lake Kallio-Kourujärvi study site (r = 0.42). Spring floods transport autochthonous organic matter and nutrients into these lakes. However, rainfall during the growing season also transfers significant amounts of nutrients and organic matter from the catchment into the lake - leading to enhanced accumulation rate of organic matter (De Stasio et al., 1996; Tian et al., 2011). This mechanism is supported by the high correlations between the precipitation of the growing season and organic matter accumulation in Lake Kallio-Kourujärvi and Kalliojärvi. The C/N values from the sediment record of Lake Kallio-Kourujärvi, varies between 19 and 22 (Paper III), highlight the importance of transported organic matter of terrestrial origin (Meyers and Ishiwatari, 1993; Paper III).

Positive correlations between biogenic matter accumulation and precipitation were not observed in the records of Lake Kuninkaisenlampi (Paper I). The explanation for the difference could lie in the trophic status. Lake Kuninkaisenlampi is located in an area with fine grained tills in the catchment (Lintinen, 1995; Maankamara – DigiKP, 2015), where naturally high trophic levels through nutrient rich catchments are expected

(Kauppila et al., 2012; Tammelin and Kauppila, 2015; Tammelin et al., 2017). At present Lake Kuninkaisenlampi is europhic while both, Lakes Kalliojärvi and Kallio-Kourujärvi, are oligotrophic or mesotrophic (HERTTA database).

In the lakes with a low trophic status, the autochthonous production is controlled by the nutrient supply. When the available nutrients are used in the littoral zone and surface waters after the stratification, the production ceases (Bradbury, 1988; De Stasio et al., 1996). Increased precipitation could provide an additional boost for biogenic production due to a nutrient pulse. Furthermore, heavy rain events like summer and autumn storms can transport terrigenous organic matter and nutrients from the catchment (Paper II). The fluctuations of organic matter accumulation in an oligotrophic like Lake Kallio-Kourujärvi reflect the changes in annual total precipitation and summer precipitation (Paper II) and can be considered as a proxy for past precipitation variability. The organic matter record of Lake Kalliojärvi has a very high potential for such use as well (Figure 9). The organic production in the hyper eutrophic Lake Kuninkaisenlampi, however, is not controlled by the nutrient supply (Paper IV). Furthermore, the Lake Kuninkaisenlampi basin has a connection to the adjacent and larger Lake Muuruvesi basin with the same water level. It is very likely that surface waters change between these two basins and thus Lake Kuninkaisenlampi organic matter sedimentation does not necessarily only reflect the organic production in the small Kuninkaisenlampi basin (Paper IV).

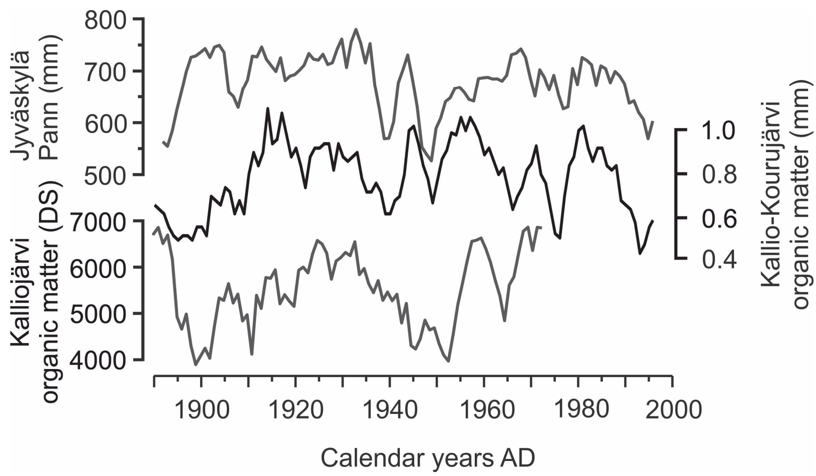

Figure 9. Annual precipitation (Pann) recorded in Jyväskylä meteorological station and organic matter accumulation in Lakes Kallio-Kourujärvi and Kalliojärvi (5-year moving average) suggest that the annual organic matter accumulation in the lakes with low trophic status is sensitive to precipitation. DS = dark sum, acquired using an image analysis technique reflecting the annual accumulation of organic matter.

The relationship between organic matter accumulation and temperature changes appears to be more complex (Paper II). Periods of both positive and negative correlations were observed when Lake Kallio-Kourujärvi organic matter accumulation and temperature records were studied (Paper II). Haltia-Hovi et al. (2007) reported decrease of organic matter accumulation in Lake Lehmilampi during MCA is in accordance with the Lake Kallio-Kourujärvi record (Paper II). In addition the Lake Korttajärvi record show decreased sedimentation rate of both clastic and organic matter for MCA period (Tiljander et al., 2003). Although autochthonous production benefits from longer ice-free period related to increased water temperatures (Magnuson et al., 2000; Tian et al., 2011), and longer growing season (Park et al., 2004), increased water temperature also leads to more efficient organic carbon mineralization (Gudasz et al., 2010) and organic matter degradation. Furthermore, especially spring temperature controls the length of spring overturns, during which the nutrients from hypolimnion upwell to the epilimnion. Elevated temperatures lead to more stable and prolonged stratification (Jankowski et al., 2006; Sobek et al., 2009), which restricts the availability of nutrients that are critical for algal populations (De Stasio et al., 1996; Park et al., 2004). Warmer temperatures may potentially lead to decreased organic matter content in the sediment sequence, through ceased production and increased degradation. It is possible that the consequence of increased temperature is reverse if the nutrient supply would be enhanced for example due to increased precipitation. Furthermore, increased organic matter degradation due to higher temperature related to diminished transport of terrigenous organic matter and nutrients due to decreased precipitation causes reduced organic matter sedimentation rate. Dryer and warmer conditions during MCA (Helama et al., 2009, 2014) are thus well in line with this interpretation of the organic records of Finnish lakes (Tiljander et al., 2003; Haltia-Hovi et al., 2007; Paper II).

5.4 Clastic matter accumulation in the lakes

The minerogenic matter in the sediments of small boreal, post-glacial lakes originates mostly from the catchment and is transported into lakes mostly by rivers and streams. Catchment erosion is controlled by climatic and environmental factors. Most significant aspect of hydrological cycle is the episodic melting of snow, which lead to increased soil erosion in the catchment, but also in river channels through increased river discharge (O'Sullivan, 1983; Renberg, 1981). The recent sediment trap study from the Lake Nautajärvi site with clastic-biogenic varves highlights the importance of catchment erosion during the spring floods (Ojala et al., 2013). The high correlations observed between minerogenic clast accumulation and maximum spring floods (Paper I) support the relationship between catchment erosion and spring flood. However, the amount of erosion is controlled by the catchment characteristics; topography, soil type and its resistance for erosion, the amount and distribution of vegetation, which binds the soil and protects from surface erosion as weel as anthropogenic activities which have a tendency to increase catchment erosion rates.

Different records indicate that the catchment dynamics plays a very significant role in regulating the response of varves in climatic forcing (Tiljander, 2003; Ojala and Alenius, 2005; Haltia-Hovi et al., 2007; Paper I; II; III; IV). Catchment composed of coarse moraines and gravels are less susceptible for erosion during runoff season than those containing fine-grained sediments. One example is the Lake Kallio-Kourujärvi, located in the area of coarse moraine ground and gravel formations, sparse with fine minerogenic matter. The water volumes released from snow pack are simply not enough to create run-off and discharges strong enough to transport the coarser grained mineral particles until human activities improved the supply of fine-grained material. Therefore clastic lamina formation does not occur in the lake until very recent times.

Enhanced minerogenic matter accumulation and thicker clastic laminae from several lakes are suggested to occur through increased snow accumulation and consequently enhanced spring season runoff (Haltia-Hovi et al., 2007; Ojala et al., 2005; Tiljander, 2003; Paper IV). However, recent studies (Paper I; IV) show that this logic cannot be generalized to all sites that accumulate clastic-biogenic varves, because the catchment properties and sedimentation dynamics can vary significantly within just tens of kilometers. The varve records from three lakes (Kantele; Kuninkaisenlampi; Linnanlampi) in eastern Finland contradict with the previous studies. The enhanced minerogenic matter accumulation occurs systematically during the periods of low winter precipitation (Paper I).

Further investigation shows that these results do not challenge the earlier results but instead, stress the previously discussed importance of case-specific understanding of the sedimentary environment. The Lake Kantele, Kuninkaisenlampi and Linnanlampi are located in the region of fine-grained tills that are very sensitive to frost formation (Lintinen, 1995; Maankamara – DigiKP, 2015). Decreased snow accumulation leads to increased frost formation (Stadler et al., 1996; Hardy et al., 2001)**.** Deeper ground frost but also longer duration of frost is formed as a consequence of lower snow accumulation (Granberg et al., 1999; Hardy et al., 2001; Lindström et al., 2002). The water released from snow melt during spring is not infiltrated in the frozen ground, the surface run-off is increased, which leads to enhanced catchment erosion (Johnsson and Lundin, 1991; Hardy et al., 2001; Ojala et al., 2013). The frost sensitivity could explain why these lake catchments seem to be sensitive to decreased snow accumulation instead of the actual water volume in the snow pack.

The Lake Kalliojärvi (paper III) as well as the previously investigated Lake Korttajärvi (Tiljander, 2003) and Nautajärvi (Ojala, 2005) are located on catchments dominated by sand moraines which are not particularly sensitive to frost formation (Maankamara – DigiKP). Such catchments are apparently controlled by the erosion caused by the actual amount of released water unlike the lakes on fine-grained tills. The catchments of these lakes do include fines grained mineral matter such as previous lake sediments, gyttja, clays and silts, which are prone to erosion during runoff. However, they are obviously not enough to cause such inverse relationship between snow accumulation and clastic lamina thickness as indicated by the three lakes on fine-grained moraines.

Fine-grained tills not only provide wealth of erodible minerogenic matter but also are generally rich in nutrients. The lakes on the watercourses on the region of fine-grained tills are having high trophic status varying nowadays from eutrophic to hyper eutrophic. The area is strongly cultivated, but recent studies show that the hyper eutrophic levels are not the outcome of human actions only, but rather human actions are concentrated to areas that are naturally rich in nutrients (Kauppila et al., 2012). The recent studies (Kauppila et al., 2012; Tammelin et al., 2017) show that these lakes are naturally eutrophic, which provokes intensified anoxia in the lake bottom waters through bacterial decomposing of organic matter. However, in many cases land use has been the primary reason for hypolimnetic anoxia (Jenny et al., 2016a; 2016b). Intensified oxygen deficiency further enhances preservation of the deposited varve structures. Not only the availability of fine-grained matter but also the tendency for eutrophic lake status at the area can contribute to the increased occurrence of lakes with varved sediments.

The large number (12) of varved lakes found from this rather small region can be an outcome of the generally anoxic conditions in addition to existence of erodible fines (the search resources were not especially concentrated to this region). The understanding of catchment dynamics can be valuable, when choosing lakes in order to study certain climatic aspects.

5.5 Solar forcing of varve characteristics

The role of solar activity variation on Earth's climate has been discussed over past decades. The Sun's role in climatic fluctuations has been stressed in a variety of spatial and temporal scales (Beer, 2000; Bond et al., 2001; Marsh and Svensmark, 2003; Gray et al., 2010; Jiang et al., 2015; Ojala et al., 2015). First indications of solar forcing on varve formation were reported already in the 1960's from several lakes in Siberia (Anderson, 1961). Since then, solar variability is reported to influence varve characteristic with different periodicities at varying time intervals (Anderson, 1993; Vos et al., 1997; Haltia-Hovi et al., 2007; Martin-Puertas et al., 2012; Czymzik et al., 2013; Ojala et al., 2015). A wide focus on varve records with respect to solar activity changes has been invoked in order to better assess the Sun's role in climate change and fluctuation in annual to millennial scales. As a result, solar activity as a forcing factor on varve formation has been confirmed from many Fennoscandian lakes (Haltia-Hovi et al., 2007; Ojala et al., 2015; Paper IV). Satellite measurements have indicated a TSI change of 1W/m2 (about 0.1 %) related to 11-year Schwabe cycle equivalent to global temperature change of less than 0.1°C (Gray et al., 2010; Lean et al., 2005). However, variation from 4 to 8 % is measured in the ultraviolet (UV) range of light (Lean et al., 2005, 1997). Furthermore, larger regional temperature variations are indicated, which suggests that strong feedback mechanisms that amplify these small changes are involved. So called top-down or bottom-up mechanism are proposed to link the small variation in TSI to the climate. Top-down mechanism involves changes in absorption of solar UV radiation through ozone in stratosphere that leads in a large meridional temperature gradient especially during winter. As a consequence, strong westerly jet is induced which, through interaction with atmospheric waves, can communicate the changes in solar radiative variation downward to the troposphere (Ineson et al., 2011; Kodera and Kuroda, 2002). Bottom-up mechanism is suggested to mediate the solar variation influence on climate through strengthened hydrological cycle which results from heating of the ocean and following enhanced latent heat flux (Meehl et al., 2008).

Even further interactions between hydrological cycles and catchment dynamics are required to mediate the solar forcing in varve characteristics. These processes are quite regional varying significantly with respect to site-specific factors (Paper I; IV). In Finland, varve records from Lake Lehmilampi (Haltia-Hovi et al., 2007), Nautajärvi, Korttajärvi (Ojala et al., 2015) and Kuninkaisenlampi (Paper IV) have been reported to be sensitive to solar variations. In these varve records, increased clast influx consistently occurred during low solar activity (Haltia-Hovi et al., 2007;

Ojala et al., 2015; Paper IV). However, it seems that solar activity is communicated to the lakes through quite different mechanisms. In the Lake Nautajärvi and Lehmilampi records, the enhanced erosion rates are related to lower winter temperatures, prolonged cold season and uninterrupted snow accumulation (Haltia-Hovi et al., 2007; Ojala et al., 2015). The results contradict the mechanisms suggested for Lake Kuninkaisenlampi where intensified frost, followed by the cold winter temperatures and decreased winter precipitation, is suggested to control the rate of seasonal catchment erosion (Paper IV). However, these interpretations do not rule out each other but only highlights the regional differences and importance of the catchment to lake sedimentation dynamics.

The Lake Kuninkaisenlampi catchment is sensitive to frost formation that is controlled by the snow accumulation and winter temperatures (Paper I, IV). Enhanced catchment erosion during low solar activity thus suggests colder and dryer winter conditions. Such atmospheric pattern is related to frequent and intensified atmospheric blocking over Northern Europe. Persistent winter atmospheric blocking coincides with low solar activity (García-Herrera and Barriopedro, 2006; Barriopedro et al., 2008; Woollings et al., 2010; Moffa-Sánchez et al., 2014), which is a likely link mediating the solar variation to frost formation and catchment erosion at Lake Kuninkaisenlampi. Although Lakes Nautajärvi and Korttajärvi are suggested to be sensitive to enhanced snow accumulation, this does not exclude the same atmospheric pattern controlling the catchment dynamic at these two sites as well. Colder springs related to blocking conditions could lead to shorter and more intense spring floods and following increased erosion.

A 1000-year periodicity that appears in the atmospheric $\Delta^{14}C$ records (Stuiver and Braziunas, 1993) as well, are found from the Lakes Nautajärvi, Korttajärvi (Ojala et al., 2015) and Kuninkaisenlampi (Paper IV), which suggests solar variation as an important driving mechanism in climate oscillation in millennial time scales. The 1000-year cyclicity is documented from several paleoclimate records from all around the world from the Arctic (Stuiver et al., 1995; Hu et al., 2003) to low latitudes (Chapman and Shackleton, 2000; Nederbragt and Thurow, 2005). Shorter periodicities from 50 to 90 years and from 90 to 140 years are related to Gleissberg solar cycle that has a wide frequency band (Stuiver and Braziunas, 1993; Peristykh and Damon, 2003; Braun et al., 2005). The 140- and 160-year cycles displayed in Lake Kuninkaisenlampi clastic lamina record have been found in a Holocene temperature record (Ogurtsov et al., 2002). The 140-year cycle is explained as a longer expression of Gleissberg cycle, while the 160-year cycle is likely a higher harmonic of Gleissberg cycle. In addition, the 200- and 400- year oscillations in Lake Kuninkaisenlampi (paper IV) and in Lake Korttajärvi (Ojala et al., 2015) varve records most likely results from Suess solar cycle and its' multiple, respectively (Stuiver and Braziunas, 1993; Braun et al., 2005).

The spectral analysis indicates that Lake Kuninkaisenlampi erosion is especially sensitive to impacts of low solar activity on Earth's climate system, because the two records show most prominent coherency at times of grand solar minima (Paper IV). Frost formation is sensitive to decreased snow accumulation and cold temperatures, which occur frequently during atmospheric blocking instead of abundance of snow. Therefore this is well in line with the sensibility of the Lake Kuninkaisenlampi time series to solar variation.

5.6 Atmospheric circulation patterns reflected in varve characteristics

North Atlantic Oscillation (NAO) is a very important atmospheric pattern influencing winter climate in northern Europe (Hurrell and Loon, 1997; Slonosky et al., 2001; Uvo, 2003). A positive NAO phase, indicated by enhanced pressure difference between Azorean high and Icelandic low, leads to stronger westerly airflows. Westerly winds transport warm and humid air over Fennoscandia which, during winter, is manifested as increased snowfall (Chen and Hellström, 1999; Uvo, 2003; Hurrell and Deser, 2009; Paper III). The importance of NAO on Fennoscandian climate is supported by several varve records that are reported to reflect NAO variability (Ojala et al., 2015; Paper III). Lake Kalliojärvi (Paper III), Korttajärvi (Tiljander, 2003; Ojala et al., 2015) show enhanced minerogenic accumulation related to positive NAO phases. This is explained by increased snow accumulation and consequently increased spring flood intensity (Tiljander et al., 2003; Paper III). The positive correlation between minerogenic accumulation in Lake Korttajärvi and Kalliojärvi and winter precipitation and snow accumulation support this interpretation. Nautajärvi record, on the other hand, shows decreased catchment erosion during positive NAO phase very likely related to increased winter discharge but declined spring (Ojala and Alenius, 2005; Ojala et al., 2015). However, there is no correlation between the Kuninkaisenlampi varve data and NAO reconstructions, which further higlights the varying spatial sensitivity of varved lake sediments to climate. A likely explanation for the absence of a NAO signal in the sediments of Kuninkaisenlampi compared to lakes in central Finland is the more eastern location, in addition to specific catchment characterized by fine-grained tills.

This is supported by analyses of recent meteorological data, which reveal clearly lower correlations between NAO and seasonal precipitation in central eastern Finland (Uvo et al., 2003) in comparison, for example, to coastal and eastern Finland. In the region of Lake Kuninkaisenlampi only 2 % of the variance in winter precipitation can be explained by the NAO index (coastal and eastern Finland 15-28%), which indicates different forcing mechanisms for winter climate in central eastern Finland compared to western and eastern Finland.

In addition to NAO, the Siberian high pressure system is a significant atmospheric pattern operating at northern high latitudes during winter (Cohen et al., 2001; Wu and Wang, 2002; D'Arrigo, 2005) and it has been linked to Fennoscandian climate as well (Muschitiello et al., 2013; Paper III). Strong Siberian high is related to continental cold and dry air masses (Cohen et al., 2001; García-Herrera and Barriopedro, 2006) and colder autumn temperatures (Yu and Harrison, 1995). Lake Kalliojärvi Fe/Mn ratio and reconstructed oscillation of Siberian high intensity display strong similarities, which highlights the importance of Siberian high on Finnish climate (Paper III; Figure 10). An atmospheric pattern with a strong continental high pressure and consequent atmospheric blocking is suggested to influence the temporal extent of Baltic Sea ice formation (Koslowski and Glaser, 1999; Tarand and Nordli, 2001). Early freezing and late melting of ice cover in small lakes such as Lake Kalliojärvi would cause a prolonged stratification and consequent enhanced oxygen deficiency manifested in high Fe/Mn ratio. This mechanism could explain the link between Siberian high and Lake Kalliojärvi redox conditions.

Also the clastic lamina record from Lake Kuninkaisenlampi is in a good agreement with a strong Siberian high reconstructed from several tree-ring records from Northern Hemisphere (D'Arrigo, 2005) from 0 to 350 years BP (Figure 10). Lake Kuninkaisenlampi record is shown to be particularly sensitive to cold and dry winter conditions (paper I, IV) which are related to solar forcing and atmospheric blocking. In combination the increased Atlantic blocking and strong Siberian high cause cooler winter temperatures and precipitation (García-Herrera and Barriopedro, 2006; Moffa-Sánchez et al., 2014). Therefore, Atlantic blocking and the strength of the Siberian high pressure cell may be related to each other in a way that Atlantic blocking might control the spread of the Siberian high especially at its western margin.

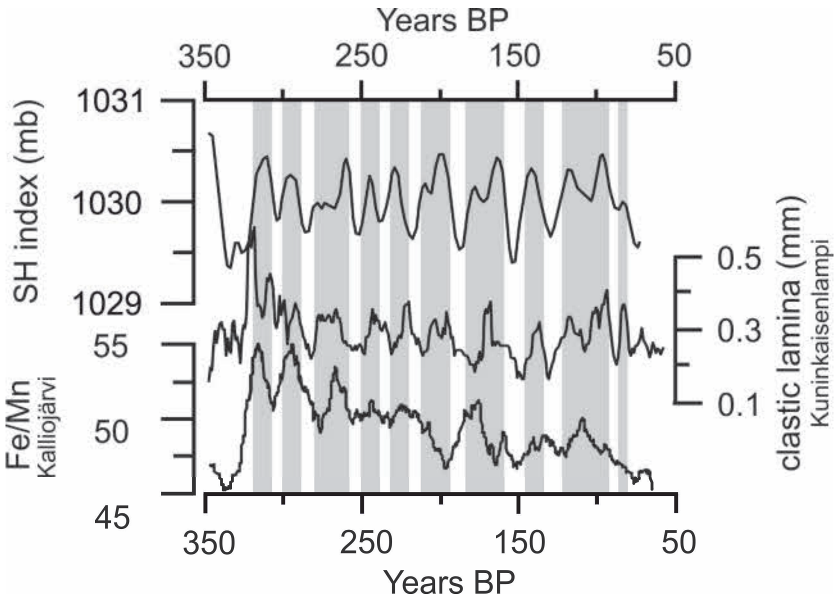

Figure 10. Reconstructed variation of Siberian high (D'Arrigo et al., 2005), clastic lamina thickness (CL) variation from Lake Kuninkaisenlampi (Paper IV) and redox changes from Lake Kalliojärvi (Paper III) reflected as oscillation in Fe/Mn ratio show similar trends. The shadings highlight the periods of strengthened Siberian high.

Preexisting cold anomalies caused by atmospheric blocking of the Eurasian continent are suggested to be an important precondition for the amplification of Siberian high in the eastern side of the Eurasian continent (Takaya and Nakamura, 2005a; 2005b). Similar mechanisms could operate in the western margin as well. Atmospheric blocking in the Atlantic is suggested to be responsible for lower temperatures in Northeastern Europe (García-Herrera and Barriopedro, 2006; Moffa-Sánchez et al., 2014), which could favor amplification and strengthening of Siberian high at its western margin. Interestingly, evidence of solar forcing on the Siberian high pressure cell has been reported for the GISP2 ice core potassium record, which showed a 80-90-year periodicity related to the solar Gleissberg cycle (Meeker and Mayewski, 2002). Siberian high oscillation is not reflected in the Si/Ti ratio of Lake Kuninkaisenlampi record probably because the high trophic status of the lake and high biogenic production. In addition, the connection to the adjacent larger lake decreases significantly the redox conditions sensitivity to reflect ice cover duration. The Lake Kalliojärvi minerogenic matter accumulation in turn, is more sensitive to variation in snow accumulation than to Siberian high.

5.7 Potential and problems of varve records in paleoclimatological and environmental reconstructions

The varve records studied show that there is great potential in varve records for diverse uses in investigating the past climate and environmental changes. A good chronological accuracy and seasonal to annual resolution support their use in order to study rapid environmental change (Ojala et al., 2012; Paper I; II; III; IV). However, varve records are in most cases sensitive to several different forcing mechanisms even within a small region. This highlights the importance of studying and understanding the lake catchment to lake sedimentation dynamics in detail in order to make interpretation related to past climate. The proxy sensitivity of the lake depends on the geographical location but the catchment characteristics are equally important. The statistical and multiproxy approach from several lakes suggests that the characteristics of the lake varve records depend on catchment type (Paper I; II; III; IV). Not only does it control the varve type it also controls the proxy sensitivity. The complexity of varves as proxies of climate and environmental change, is clear. Furthermore, due to short extent of instrumental records and the lack of hydrological monitoring on the catchment of small peripheral lakes, it is very difficult to show the affect of anthropogenic activities on the lake catchment have changes the proxy sensitivity of each varve record.

Human actions on the lake catchment must be kept in mind when investigating varve records in Finland since the 16th century. The organic content of varves starts to increase in Lake Kallio-Kourujärvi, Kalliojärvi and Kuninkaisenlampi between 16th and 17th century, most likely related to early human settlements, slash and burn cultivation and pasturing. The increased human induced erosion occurs significantly later, during between 18th and 19th century. Erosional peaks caused by intensified land use in the catchments of Lake Kalliojärvi (Paper III), Kuninkaisenlampi (Paper I; IV) and Linnanlampi (Paper I) show only short-lived elevated erosional rates lasting a few years, after which varve thickness returned to the previous levels. This indicates, that although a single erosional peak should be interpreted with care, the natural influence on varve characteristics dominates the varve records before and after the human residency on the catchments. Furthermore the correlations with hydrological and climatic parameters suggest that despite the human induced changes, the lakes catchments do still respond to climate change.

With increased understanding of the regional and catchment influence on varve proxy sensitivity, it can be possible in future to choose a proper lake for a certain research question instead of wasting resources in order to study a long varve record and learn that the question cannot be answered, after all. However, this requires more detailed understanding of catchment processes. Furthermore, much of the internal lake processes are not well understood, which can affect significantly the distribution of sediments in the lake bottom. The complexity of organic matter preservation and redox changes as well as phosphorous cycle and nutrient availability in biogenic varve proxy should be investigated in detail, although the results of this study suggest that biogenic laminae are a potential and promising proxy for growing season precipitation reconstruction. However much work remains to be done in order to understand the processes by which climatic variation influences varve characteristics.

6. CONCLUSION

This thesis presented three new, well dated long varve chronologies, two of clastic-biogenic varve type and one of biogenic varve type, with temporal extent of 3000-4000 years. In addition, two recent 100-year clastic-biogenic varve chronologies were studied. The overall aim was to better understand the climatic forcing on varve characteristic and mechanisms that link climate variability to sedimentary processes. The physical varve properties were measured using image analysis technique and microfacies analysis. The varve data and climatic and hydrological data were subjected to statistical analyses that enabled identification of a series of physical mechanisms that linked climate to sedimentary processes. Comparison of the varve data and previously published NAO variability, $\Delta^{14}C$ and Siberian high strength records suggested that geographical location of the lake is of high importance and can control which atmospheric pattern the region is sensitive to. The statistical correlation between biogenic matter accumulation in the low trophic lakes and recent precipitation data from the nearest meteorological station revealed the strong relationship. In the lakes that are sparse in nutrients, autochthonous production increased as a result of enhanced precipitation. The nutrients, as well as organic terrigenous matter, are transported to the lake as a result of increased stream velocity. Such relationship was not observed from eutrophic lakes. The statistical correlation between clastic lamina thickness and winter precipitation between the studied lakes, showed spatially contrary correlations. The contradiction was explained by catchment characteristics. Generally, catchment erosion has been interpreted to be controlled by the quantity and rate of water released from snow pack during spring. The Lake Kalliojärvi record was sensitive to winter precipitation and snow accumulation that was suggested to be controlled by the North Atlantic Oscillation, of which positive phase transport humid air over Fennoscandia. However, at the region characterized by fine-grained tills, the increased minerogenic matter accumulation occurred during low winter precipitation. Fine-grained tills are very sensitive to frost formation, which has been controlled by the snow accumulation. During the melting season, water is not infiltrated to frozen soil pores and as a consequence surface run-off and catchment erosion is increased. Increased clast accumulation on the region of fine-grained tills was related to dry and cold winter conditions. In Lake Kuninkaisenlampi, located on the region of fine-grained tills, the clast accumulation was related to changes in solar activity. Frequent atmospheric blocking during periods of low solar activity was related to cold and dry winter conditions that very likely resulted in snow poor winters and longer prevalence of frost.

The results highlighted the importance of catchment dynamics in varve proxy sensitivity and revealed tight coupling between atmospheric forcing, hydro-climate and sedimentary processes in boreal lakes.

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Believe you can, believe you can’t,
Either way, you are right.
-Henry Ford-

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