Between the North Atlantic Oscillation and the Siberian High: a 4000-year snow accumulation history inferred from varved lake sediments in Finland

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Abstract

Clastic-organic varved sediments from the boreal Lake Kalliojärvi, Central Finland, record changes in snow accumulation for more than 4,000 years. The varve record was reconstructed using digital image analysis from 4,132 varve yrs BP to present with 2.2% counting error and is supported by paleomagnetic data. Two laminae are identified in a typical varve structure: i) the minerogenic lamina, which accumulates during spring as a result of catchment erosion triggered by spring floods and ii) the organic lamina, which is composed of allochthonous and autochthonous organic matter that accumulates during summer, autumn and winter. The minerogenic influx is related to variations in snow accumulation and follows the different phases of the North Atlantic Oscillation (NAO). Decreased snow accumulation is related to a weakened NAO phase. Thus the minerogenic influx record provides additional information about NAO variation. The Fe/Mn ratio is related to changes in redox conditions at the lake floor. The oxygen availability in the lake floor depends on the duration of the ice cover during winter. Strengthened Siberian High (SH) causes colder autumn and winter temperatures and therefore leads to extended duration of ice cover. Fe/Mn can be considered as a proxy for SH. The sediment record suggests pronounced, generally positive but strongly fluctuating NAO phase, from ca 4,100 to 3,200 varve yrs BP. Periods of strengthened SH are observed at 3,900-3,600, 1,900-1,500 and 1,200-750 varve yrs BP. Our study suggest that NAO and SH operates individually, are not clearly linked and do not entirely block each other.

Keywords

Lacustrine varved sediments, Northern Europe, geochemistry, paleoclimatology, North Atlantic Oscillation (NAO), Siberian High (SH), snow fall reconstruction

Introduction

Varved sediments are widely used in paleoclimatological and paleoenvironmental studies because of their precise time control and the diverse possibilities that seasonal resolution can provide such as interpretation of seasonal paleoclimatic signals and dynamics of the abrupt changes (Brauer et al., 2009; Dean et al., 1999). Small boreal lakes react particularly sensitively to climatic and environmental changes (Haltia-Hovi et al., 2007; Itkonen and Salonen, 1994; Saarni et al., 2015) and may thus record climatic variability in detail. However, a variety of catchment processes affect sedimentation. Therefore it is difficult to distinguish between climatic, environmental, and anthropogenic reasons for these changes (Gälman et al., 2006; Itkonen and Salonen, 1994). Major human impact is observed in Central Finland only after Medieval times (Orrman, 1991). The lake record from remote location with minimal human land-use provides reliable information about the past climatic and environmental changes.

There are numerous proxy studies concentrating on climate change during the last millennium (Corella et al., 2012; Jones et al., 2001; Luterbacher et al., 2004; Mayr et al., 2005;), but high-resolution studies extending beyond the last one or two thousand years are still rare. The last two millennia include climatic oscillations such as the Medieval Climate Anomaly (MCA), the Little Ice Age (LIA) and the 20th century warming. In order to discuss these fluctuations in a broader context, additional and longer high-resolution paleoclimatological studies are needed. An advantage of varved sediments is that these records potentially cover the entire Holocene (Dean et al., 1984; Martin-Puertas et al., 2012; Ojala and Alenius, 2005) and even beyond (Brauer et al., 2001; Brauer et al., 2008; Koutsodendris et al., 2011; Mangili et al., 2010; Nakagawa et al., 2012; Neugebauer et al., 2012). Our objectives are to establish a varve chronology that reaches 4,000 years back in time and to observe changes in sedimentation rate, minerogenic matter accumulation, and geochemical composition in order to infer climatic and environmental changes at the study site.

The climate in Finland is influenced by the Atlantic Ocean and the large continental landmass of Siberia. The strength and location of the continental and oceanic air masses are further influenced by the North Atlantic Oscillation (NAO; Hurrell and Deser, 2009) and the Siberian High (SH; Meeker and Mayewski 2002; Muschitiello et al., 2013). Therefore, the study site provides an excellent setting in order to study variations of the NAO and the strength of the SH. Our objective is to evaluate the role of NAO and SH on the regional climate and varve formation.

Site description

Lake Kalliojärvi is located at 63°13'N, 25°22'E in the municipality of Viitasaari, Central Finland. It is an elongated lake with a surface area of 0.15 km^2 and a drainage basin of 6.3 km^2 (Figure 1). The altitude of the lake is 121 m above sea level and its maximum water depth is 12.3 m. There are two major inlets in the north-west part of the lake and an outlet in the south-eastern corner. Lake Kalliojärvi was formed during the retreat of the Weichselian ice sheet when it was isolated from the Ancylus Lake, an early stage of the Baltic Sea. The exact timing of the isolation is unknown (Eronen and Haila, 1990).

Lake Kalliojärvi is situated in a catchment composed of former lake sediments, Quaternary till, *Carex* and *Sphagnum* peat and outcrops mainly of plutonic rocks such as granites, granodiorite and gabbro (Nykänen, 1962). The region belongs to the boreal vegetation zone with coniferous forests dominated by pine and spruce. There is no permanent human settlement in the vicinity of the lake.

The annual mean temperature in the study area is approximately 2°C. The mean temperature of the coldest month (January) is –9°C and in the warmest month (July) +16°C (Helminen, 1987). Annual precipitation is between 600 and 650 mm of which about one third precipitates as snow (Solantie, 1987). The lake is ice-covered for about 6 months each winter (Kuusisto, 1986).

Methods

Coring

Lake Kalliojärvi was cored in the deepest part of its basin (Figure 1) through a 40 cm thick ice cover in March 2008 and 2012. The coring was performed manually with a rod-operated piston corer, which was slowly and continuously pushed into the sediment to prevent disturbances in the sediment cores. Two parallel cores (KAL-1 from 2008 and KAL-3 from 2012) were obtained a few meters apart in 3.0 m long PVC tubes with diameters of 6.4 cm recovering about 2.4 and 2.1 m of sediment, respectively.

Undisturbed surface samples with an intact water/sediment interface were obtained using Limnos corer (Kansanen et al. 1991) and mini ice-finger technique (Renberg, 1981; Saarinen and Wenho 2005). Wedge shaped mini ice-finger, with length of 35 cm, was pushed slowly into the surface sediments obtained with Limnos corer. Topmost sediments and the water/sediment interface were frozen around the mini ice-finger using dry ice. Several parallel surface samples were taken in the vicinity of the location of the piston coring.

Sample preparation and impregnation in epoxy

Sediment cores were opened carefully in the laboratory with a circular saw, a wire and a knife. The fresh sediment surface was cleaned with a glass blade. Subsamples for the varve component study and element detection were taken from the core KAL-1 in the manner described by Haltia-Hovi et al. (2007). The 2.3 m long sediment sequence was subsampled continuously for sediment embedding using 11 cm long aluminum molds with 1.5 cm overlap.

All together 24 subsamples were impregnated in Spurr low viscosity epoxy resin following the water-acetone-epoxy exchange method (Lamoureux, 1994; Tiljander et al., 2002). Sediment was considered to be sufficiently dehydrated when water content of the acetone was <0.5% (Haltia-Hovi et al., 2007; Moran et al., 1989). A small amount of acetone was added in the first two epoxy exchanges (10 exchanges in total) in order to improve impregnation (Pike and Kemp, 1996). The samples were cured at 60°C for 48 h. The impregnated subsamples were polished using a surface-grinding machine. A thin slab of 1.8 mm was cut off from the polished side of each subsample for radiographs and μ-XRF studies.

Radiography of the samples

The 1.8 mm slabs were analyzed using medical X-ray equipment on Agfa Structurix DW/D7 films. The focal distance was set to 50 cm and focus size to 0.1 mm. An electric current of 10 mA and voltage of 20 kV were used with 8 s of exposure time. With each radiograph, a calibration wedge made from thin glass slips, was used in order to enable correlation between the images. Radiographs were digitized using a Canon scanner with a resolution of 1000 dpi (CanoScan 9900F).

Varve counting

Digital image analysis of radiographs is a rapid and objective method to analyze varve structures (Ojala and Francus, 2002; Petterson et al., 1999) and therefore it was used to count and record physical properties of the Lake Kalliojärvi varves. Radiographs of each subsample block were calibrated and equalized by adjusting brightness and contrast until the gray scale values in the calibration wedge were on the same level. A one-pixel wide analytical line (gray scale value 0) was drawn perpendicular to the varve structure and the varve boundaries were defined at the lowest deflection points on the gray scale value curve (Ojala and Francus, 2002). A manual revision of the automatic varve counts was made using X-ray images and polished subsample blocks under a binocular. Varve chronology is based on a single varve count, however, three individual counts were performed for comparison and to calculate error estimate. For each count, a new analytical line was drawn.

Two varve parameters were measured: total varve thickness (VT) and light sum (LS). Dense material such as minerogenic laminae absorb x-rays and cause the lighter shades on the film compared to less dense organic material. Density variations are recorded as variable grey-scale values (0-255). The area below the X-ray density curve in each varve was calculated to acquire a relative Light Sum (LS), which reflects accumulation of minerogenic matter (Dean et al., 2002b; Ojala and Francus, 2002).

Magnetic measurements

Low field magnetic susceptibility (κ_{LF}) was logged in order to enable core correlation. The cores KAL-1 and KAL-3 were logged at 2.0 mm intervals from freshly opened and cleaned sediment surfaces covered with a plastic film. An automatic measuring track was used with a Bartington MS2 susceptibility meter and an MS2E1 spot reading sensor.

The core KAL-3 was sampled for paleomagnetic measurements. Paleosecular variation was measured to support the varve chronology. Plastic sample boxes with a volume of 6.1 cm^3 were used with 3 cm sample intervals. The natural remanent magnetization (NRM) was measured with a Molspin portable Minispin spinner magnetometer. Magnetic inclination and relative declination were calculated from NRM data.

Micro X-ray fluorescence

The impregnated and 1.8 mm thick slabs used for radiographs were also used for major element determination using micro X-ray fluorescence (μ-XRF) techniques in order to allow direct comparison of geochemical and micro-facies data (Brauer et al., 2009; Shanahan et al., 2008). Analyses were performed with a vacuum-operated EAGLE III XL μ-XRF spectrometer on a scan line, using a step size of 100 μm (spot size of 123 μm), 50 s counting time, a tube voltage of 40 kV, and a current of 350 μA. High-resolution element scanning was used to provide several data points from individual seasonal laminae. Resulting intensities of elements such as Mg, Al, Si, K, Ca, Ti, Mn, and Fe are expressed semi-quantitatively as counts per second (cps).

Results

Sediment description

The Lake Kalliojärvi sediments represent clastic-organic varves comparable to previously reported varve types (Haltia-Hovi et al., 2007; Ojala and Alenius, 2005; O'Sullivan, 1983). Each varve year begins in spring when snow melt causes flooding and increased erosion in the lake watershed. Eroded clastic material is transported into the lake and deposited to form the first distinct lamina with a high mineral content and corresponding high density (Figure 2). Minerogenic clasts show graded bedding with largest grains of 25 μm in diameter, as observed by microscope analyses. The boundaries of the laminae are clear. The second lamina consists of organic material of autochthonous and allochthonous origin produced during the growing season. The third lamina is very thin, nearly black and consists of amorphous organic material that is settled down in quiet waters under ice cover. The boundary of the second and third lamina is not very clear, and the lamina can be distinguished only microscopically. In radiographs the second and third laminae cannot be distinguished due to similar densities. Occasionally, an additional clastic lamina is intercalated in the organic laminae caused by recurrent snowmelt during spring periods or heavy rainfall events in summer and autumn.

Establishment of the varve chronology

The top of the varve chronology was constructed from the mini ice finger samples and was anchored to core KAL-1 by linking the marked varves from mini ice finger samples and x-ray images from core KAL-1. The two cores (KAL-1 and KAL-3) were correlated using low field magnetic susceptibility (κ_{LF}; Figure 3). The similarity of both records suggests a comparable sediment accumulation throughout the deepest part of the basin (Petterson et al., 1993; Tiljander et al., 2002).

In total 4,132 varves were counted. Varve counting errors were estimated as lower or higher counts in relation to the average of the three repeated varve counts made by the same analyst (Lotter and Lemcke, 1999). The cumulative counting error is estimated to –2.2% (91 varve years) and +2.1% (87 varve years) (Figure 4). However, counting differences vary in different intervals of the sediment record. In the interval of poorly preserved varve structure, highest counting error is observed (7.2%). Obscured varve boundaries might be caused naturally or as a consequence of coring or subsampling. In intervals with the best varve quality, mainly found in the deepest parts of the record, all three varve counts are identical.

Generally, the counting error is comparable to other varve studies (Haltia-Hovi et al., 2007; Saarni et al., 2015; Snowball et al., 1999; Tiljander et al., 2003) and confirms the good quality of the varve record.

Validation of varve chronology

Paleomagnetic data was used to verify the validity of the varve chronology. Paleosecular variations (PSV) with most prominent inclination (γ, δ, ε, ε^1) and declination (d, e, f) features, originally described by Turner and Thompson (1981) from British lake records, were observed in the paleomagnetic record from Lake Kalliojärvi (Figure 5). The ages of inclination and declination shifts in Lake Kalliojärvi data are very close to those in FENNOSTACK (Snowball et al., 2007), a PSV master curve comprised of several well-dated Fennoscandian lake records. The small temporal lags between the dates are explained by different lock-in depths and the averaging nature of FENNOSTACK. Simultaneous occurrence of PSV features supports the reliability of the varve chronology from the Lake Kalliojärvi record (Figure 5).

Varve parameters and geochemistry

VT varies between 0.18 and 2.13 mm, average thickness is 0.52 mm, and median 0.48 mm. The correlation between VT and LS is high, *r* = 0.8. VT and LS show highest values and variabilities before 3,200 BP (Figure 6). A distinct decrease in VT and LS occurs at 3,200 and the amplitude of the variability is reduced. VT and LS show decreasing trend until 50 BP.

Two different geochemical associations can be distinguished based on similar patterns of element counts. The detrital silicate mineral (DSM) association contains Al, Ca, K, Mg, Si and Ti (Dean et al., 2002a; Shanahan et al., 2008) that show uniform patterns with each other and with LS (Figure 7). DSM association elements reach maximum values in minerogenic laminae. The redox sensitive association (RS) is comprised of Fe and Mn (Dean et al., 2002a, Shanahan et al., 2008) that show similar trends with each other. DSM and RS associations display highest values prior to 3,200 varve yrs BP. DSM association fluctuates throughout the entire record while RS association show decreasing trend after 3,200 varve yrs BP.

Discussion

Lake Kalliojärvi varves are of clastic-organic type which is common for the boreal zone (Haltia-Hovi et al., 2007; Ojala and Alenius 2005; Petterson et al., 1999; Tiljander et al., 2003). Total varve thickness (VT) is the sum of minerogenic and organic matter accumulation (Figure 2). Light sum (LS) reflects the accumulation of minerogenic components, which is related to the magnitude of spring snow-melt floods (Haltia-Hovi et al., 2007; Ojala and Alenius, 2005; Tiljander et al., 2002). The strength of spring floods is controlled by the amount of snow that is accumulated during the previous winter and by the intensity and length of the melting period (Dean, 2002a; Dean, 2002b; Snowball, 1999; Tiljander et al., 2003). Abrupt and warm spring triggers more intensive flood peak than slow melting of snow during a cool spring. Various studies have used LS as a proxy for snow accumulation (Haltia-Hovi et al., 2007; Ojala and Alenius 2005; Petterson et al., 1999; Tiljander et al., 2002); however, the limitations caused by the variation in annual flood intensity should be kept in mind.

The element concentration in the sediment is driven by physical and chemical weathering in the catchment area, atmospheric deposition and sedimentation processes. DSM association consists of elements that are constituents of silicate minerals, common in plutonic rocks that dominate the lake watershed. DSM association reflects the composition of minerogenic laminae (Figure 2; Figure 7) and, in addition to LS, is a proxy for snow accumulation and catchment erosion. A small part of Ca and Si have an organic, autochthonous origin. Ca occurs as sporadic enrichments in calcareous organisms such as molluscs, while Si is accumulated through diatom frustules. Ti neither results from biogenic production nor is sensitive to redox changes and thus can be reliably related to minerogenic flux. The high correlations between Ti and Ca (r = 0.73) and Si (r = 0.71) suggest a predominantly minerogenic origin of Ca and Si.

The redox sensitive (RS) association is composed of elements (Fe, Mn) that are enriched in organic laminae (Figure 2) and respond to changes in oxygen availability at the lake floor (Dean, 2002a). Anoxic hypolimnetic waters rich in Fe and Mn are mixed with oxygen rich epilimnetic waters during fall overturn which trigger precipitation of Fe and Mn as oxides and oxyhydroxides (Davison, 1993; Dean, 2002a; Stauffer and Armstrong, 1984). Preservation of Fe in the bottom sediments is enhanced by formation of ferric oxyhydroxide colloids or gels whereas manganese oxyhydroxides are less stable under reducing conditions (Davison, 1993; Dean, 2002a; Shanahan et al., 2008; Stauffer and Armstrong, 1984). Due to differences in sensitivity of ferric and manganese compounds to dissolve with changing oxygen availability, the Fe/Mn ratio can be used as a proxy for redox changes (Dean, 2002a; Koinig et al., 2003). Higher Fe/Mn ratio reflects decreased oxidation of bottom waters, which could be caused by prolonged lake stratification largely controlled by the duration of ice cover, shortened lake overturning or changes in the organic matter accumulation. The increased organic matter accumulation causes enhanced oxygen consumption which leads to spatially wider and faster development of anoxia on the lake floor. The effect on Fe/Mn would be similar than that caused by prolonged lake stratification. Varve thickness shows similar trends (Figure 6) and high correlation with minerogenic matter accumulation and thus it can be anticipated that there was no significant changes in organic matter accumulation. However the possible changes in oxygen consumption caused by changes in organic matter accumulation should be taken into account while observing Fe/Mn data.

LS and DSM are related to catchment erosion, and thus any processes that affect erosion rates in the lake watershed, such as changes in vegetation, can be misinterpreted as a climatic signal. The decreasing trends of LS and VT, observed in the entire Lake Kalliojärvi record reflect the general lake evolution. Gradual shallowing of the lake followed by swamp and vegetation formation prevents transportation of allochthonous material. Furthermore, the availability of erodible clastic matter in the lake catchment decreases with time. It is very likely that there were no permanent human settlements in the Lake Kalliojärvi area prior to the 16th century (Orrman et al., 1991) and early human activities such as slash and burn cultivation are not expected to affect catchment erosion significantly before the 16th century. Human-induced catchment erosion, airborne fallout and loading of nutrients may have changed element concentrations in the sediment. This should be taken into account, especially when exploring the record since the 16th century. Furthermore, major changes in erosion rate and element concentration are recognized since 100 varve yrs BP and thus the topmost sediments are excluded from discussion.

Climatic importance of North Atlantic Oscillation and Siberian High

Winter climate variability across northern and western Europe has been related to the NAO (Hurrell and van Loon, 1997; Slonosky et al., 2001; Uvo, 2003). The importance of NAO to European climate is supported by paleoclimatic reconstructions from European varved lake sediments (Cooper et al., 2008; Koutsodendris et al., 2011; Martin-Puertas et al., 2008; Olsen et al., 2012; Romero-Viana et al., 2008; Tiljander et al., 2003; Zahrer et al., 2013). A positive NAO phase leads to strengthened westerly winds that contribute warm and humid maritime air masses over Fennoscandia. This leads to warmer air temperatures and increased winter precipitation (Chen and

Hellström, 1999; Hurrell and Deser, 2009; Hurrell and van Loon, 1997; Luoto and Helama, 2010; Slonosky et al., 2001; Trouet et al., 2009; Uvo 2003) that are observed as increased LS in Lake Kalliojärvi varve record (Figure 8). The mean temperature of winter months (December-February) in Central Finland is about -8°C (Nordklim, 2002) and thus the enhanced precipitation of positive NAO phase manifests as snow accumulation despite the milder winters (Figure 8). Only unusually strong positive NAO could cause adequate winter warming that could lead to decreased snow accumulation in Central Finland due to frequent melting of snow related to increased winter temperatures. This may possibly hamper the extreme positive NAO phases in the data, however such extreme events are rare and reduction in NAO phase is generally related to decreased snow accumulation (Figure 8).

Time interval between 3,900 and 3,200 varve yrs BP is characterized by generally high snow accumulation interrupted by decadal periods of snow-poor winters. This coincides with fluctuating water levels in Scandinavian peat bogs (Gunnarson et al., 2003; Väliranta et al., 2007) and a simultaneous period of enhanced snow accumulation and rainfall in Scandinavia (Anderson et al., 1998; Borgmark 2005; Hammarlund 2003; Snowball et al. 1999; Wanner et al. 2008). This is in line with the reconstruction of St. Amour et al. (2010) suggesting a positive NAO-like atmospheric circulation conditions between 4,200 and 3,000 BP. However, we suggest a corrective that the positive NAO phase could have been interrupted several times. Cyclic occurrence of snow-poor winters suggests weakened westerly winds related to decreased NAO phase.

It can be anticipated that SH, being a significant pressure system operating during wintertime in the Northern Hemisphere (Cohen et al, 2001; D'Arrigo et al, 2005; Wu and Wang, 2002), has an influence on the climate of Central Finland, close to the Siberian continental landmasses. Muschitiello et al. (2013) have recently linked increased snowfall in Gotland, an island on the Swedish east coast, to a strengthened SH. Northeasterly winds prevail in Fennoscandia during a strong SH. Humid air is transported from the Baltic Sea region which causes increased snowfall at the western coasts of the Baltic Sea (Muschitiello et al., 2013; Yu and Harrison, 1995). The increased snowfall related to strong SH is not observed in Lake Kalliojärvi record because continental air is dry and cold prior to entering the Baltic Sea (Yu and Harrison, 1995). However SH blocks the westerly winds (Hurrell and Deser, 2009; Muschitiello et al., 2013; Yu and Harrison, 2005) which leads to colder temperatures earlier in autumn and results in early freezing of small lakes in Central Finland. Frequent blocking of westerly flows and cold temperatures are related to increased ice formation in the Baltic Sea region as well (Koslowski and Glaser., 1999; Tarand and Nordli, 2001). Stronger and prolonged ice cover on the lakes causes prolonged water-column stratification and increased oxygen deficiency, which is related to increased Fe/Mn ratio. In Lake Kalliojärvi sediments, the Fe/Mn ratio shows similar pattern with the SH intensity reconstructions (Figure 9; D'Arrigo et al, 2005; Legrand and Mayewski, 1997; Mayewski et al., 1997; Muschitiello et al, 2013) and suggests periods of strengthened SH at 3,900-3,600, 1,900-1,500 and 1,200-750 varve yrs BP.

The interactions between NAO and SH intensity are not well understood. As both are significant atmospheric circulation patterns operating on the Northern Hemisphere (Cohen et al, 2001; Hurrel and Deser, 2009), NAO and SH may interact through complicated teleconnections which are not yet understood. However, no evidence of straightforward connection exists. Arctic Oscillation (AO), being well correlated with NAO (Thompson and Wallace, 1998), could operate as a link between NAO and SH intensity. However, AO has been reported to account only 13% of variance in SH (Wu and Wang, 2002) and thus so far NAO and SH intensity should be considered relatively independent of each other (Figures 8 and 9). The increased snow accumulation due to positive NAO phase may occur regardless of strong SH. The possible explanation could be the northward propagation of SH after freezing of the Arctic Ocean (Cohen et al, 2001). As the most significant effect of SH in Central Finland is early ice formation, Fe/Mn cannot record the northward propagation of SH once the lake is frozen. The northward propagation of SH could occasionally allow the westerlies to invade over Fennoscandia which may result in a signal of positive NAO and strong SH in Lake Kalliojärvi.

Snow accumulation follows the reconstructed NAO pattern (Trouet et al, 2009) well before the 17^{th} century, but since then the NAO variation in the LS signal is lost. SH is reflected in Fe/Mn variations until the 18^{th} century. The change in proxy sensitivity very likely reflects human impact.

Conclusions

This study presents a clastic-organic varve record from Lake Kalliojärvi (Central Finland), which covers 4,132 varve years. The study site is located between Atlantic maritime and Siberian continental air masses. In respect of the paleoclimatic juxtaposition, changes in varve thickness, annual sedimentation of minerogenic matter as well as geochemical data were interpreted. Minerogenic accumulation reflects changes in snow accumulation, which is related to North Atlantic Oscillation (NAO). During positive NAO phase the strengthened westerly winds carry humid air over Fennoscandia and cause increased winter snow accumulation. Thus mineral influx can be used to acquire further information of past NAO variations. The Fe/Mn ratio yields information of redox changes. High Fe/Mn suggests increased oxygen deficiency which is caused by the prolonged water column stratification triggered by extended period of winter ice cover. Prolonged ice cover is related to strengthened Siberian High (SH) and thus Fe/Mn ratio record from Lake Kalliojärvi can be used as a proxy for SH. Our reconstructions suggest that NAO and SH operate individually and are not clearly linked with each other.

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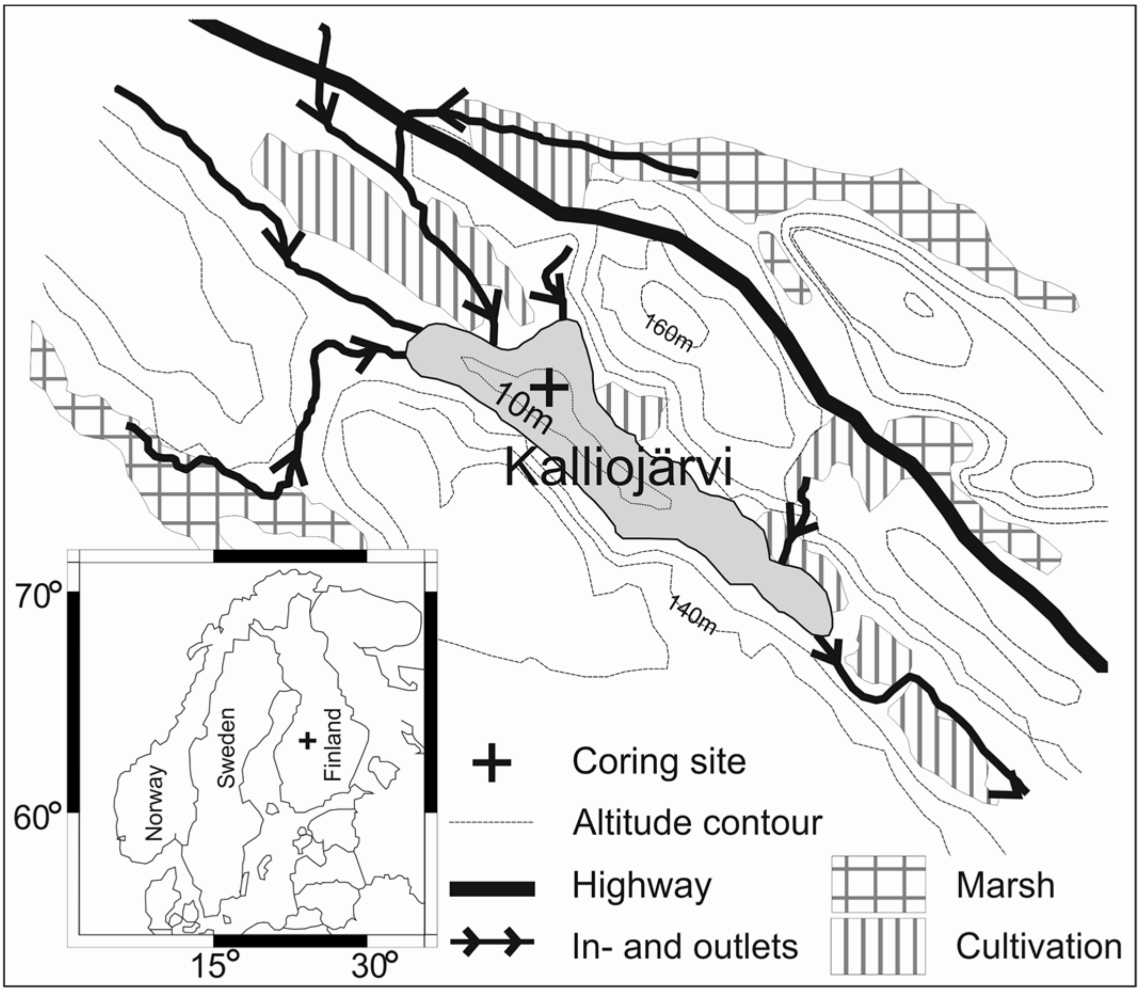

Figure 1. A schematic map showing the location of the investigated lake in Fennoscandia with a topographic map of the lake and its immediate catchment area. The coring site and the attributes of the catchment basin are provided.

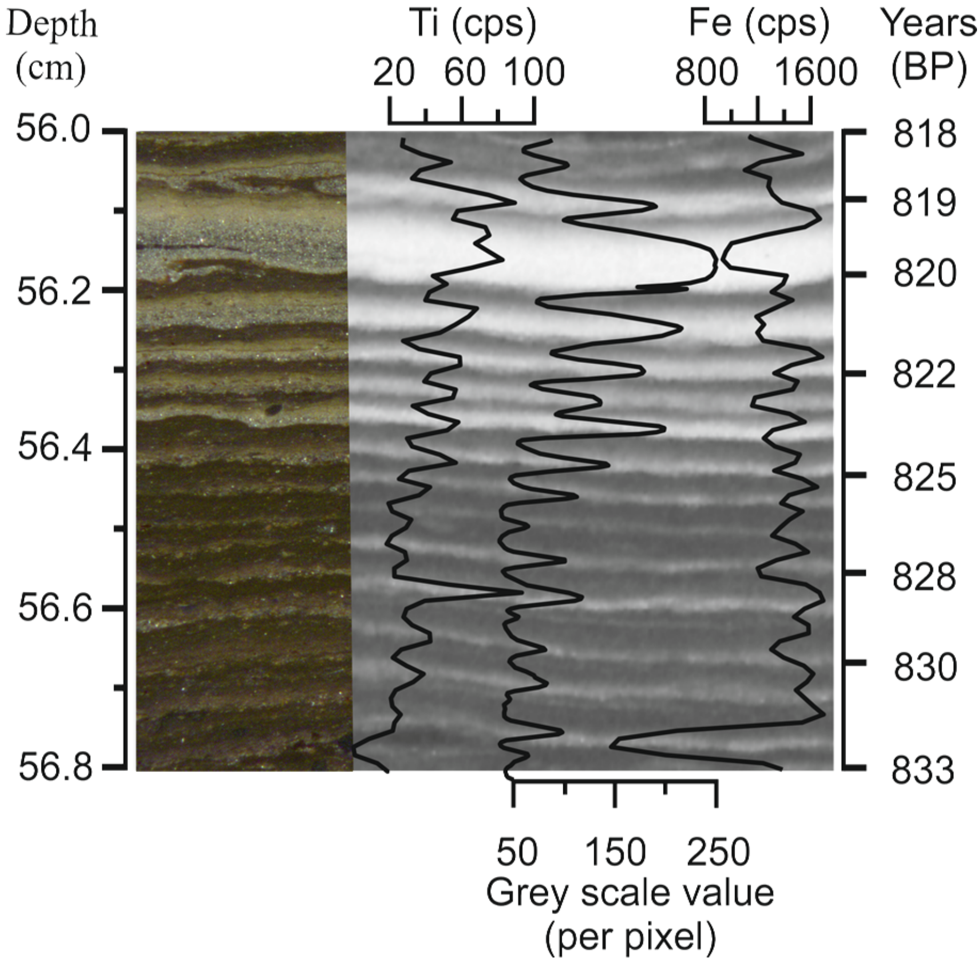

Figure 2. Microscopic image (left) of Lake Kalliojärvi varves compared to an X-ray image (right). Titanium (Ti) analyzed with μ-XRF and grey scale value show peaks in minerogenic laminae while iron (Fe) is enriched in organic laminae.

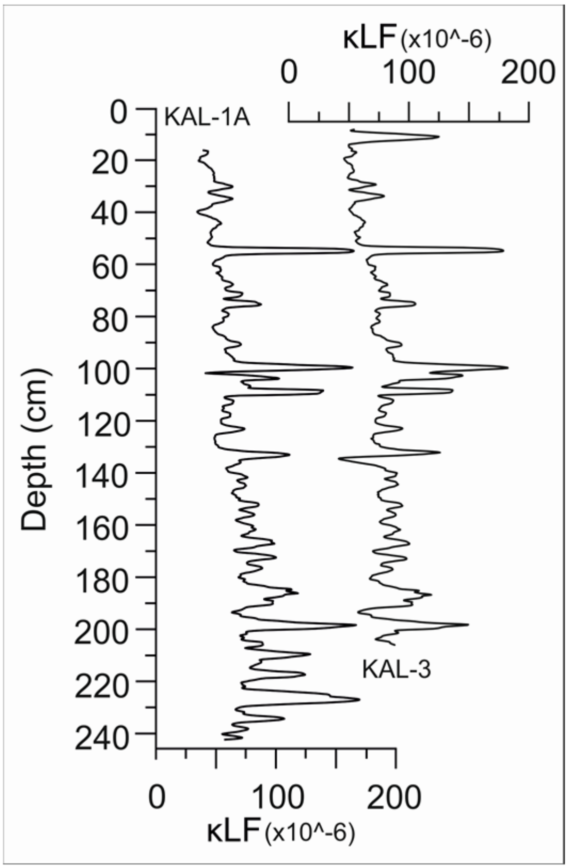

Figure 3. Low field magnetic susceptibilities (κ_{LF}) from cores KAL-1 and KAL-3.

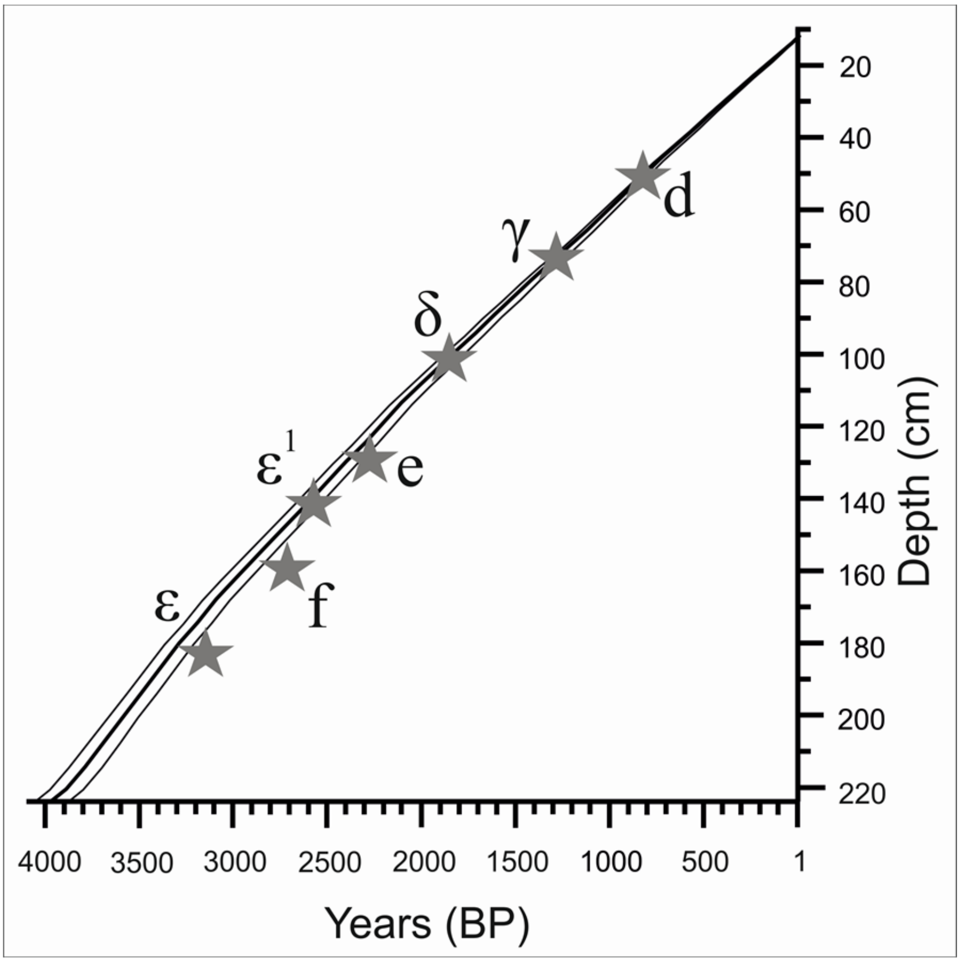

Figure 4. Error estimates of the varve chronology with ages of inclination and declination features (cf. Figure 5).

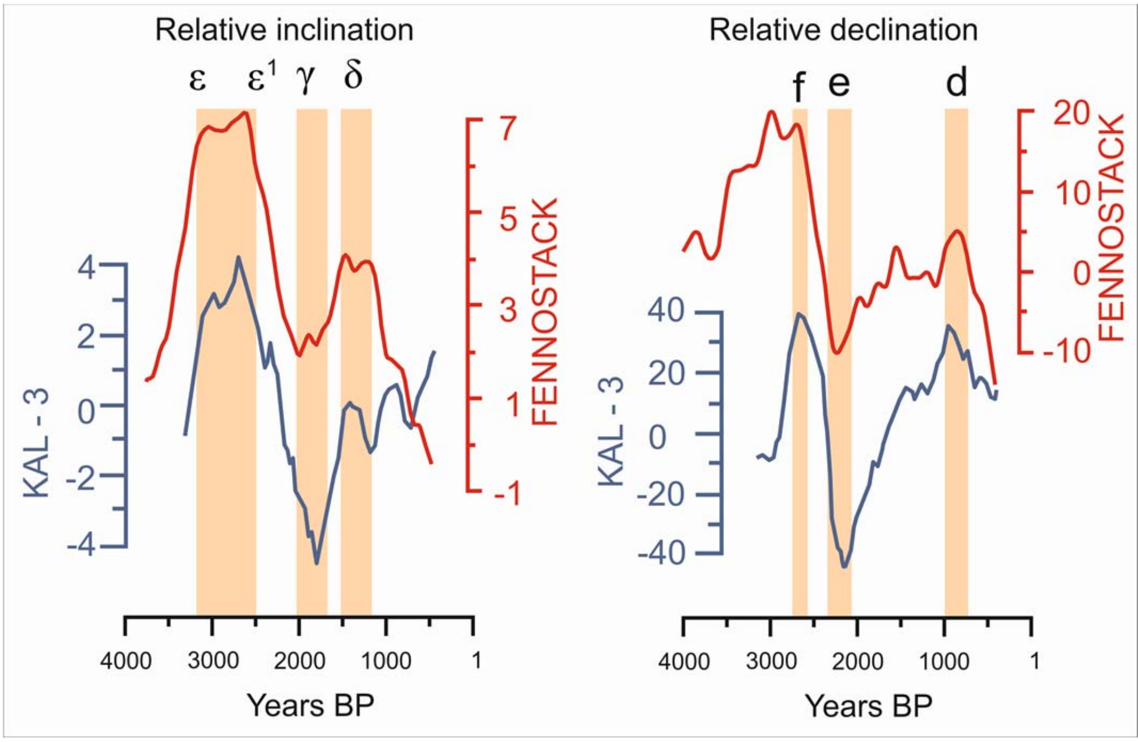

Figure 5. Paleo-secular variation from Lake Kalliojärvi compared with the FENNOSTACK master curve (Snowball et al., 2007).

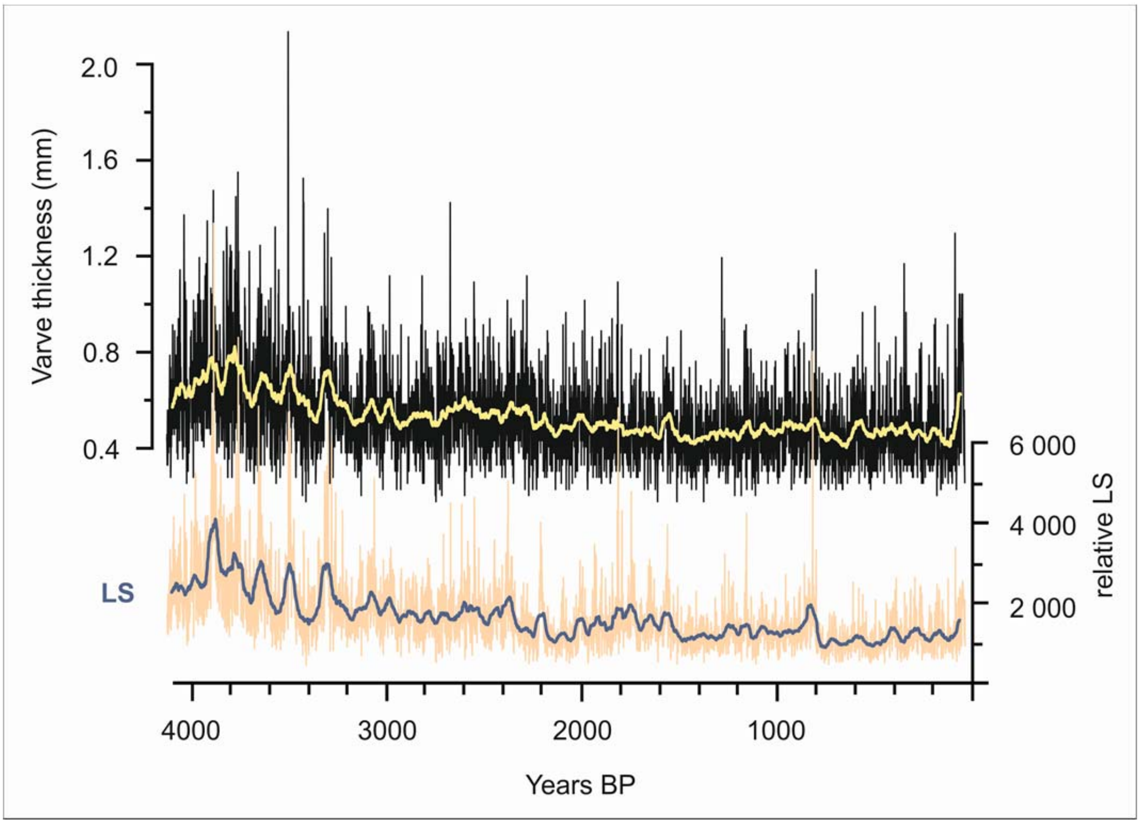

Figure 6. Varve thickness (VT), and light sum (LS) variations. The thick lines are 21-year moving averages.

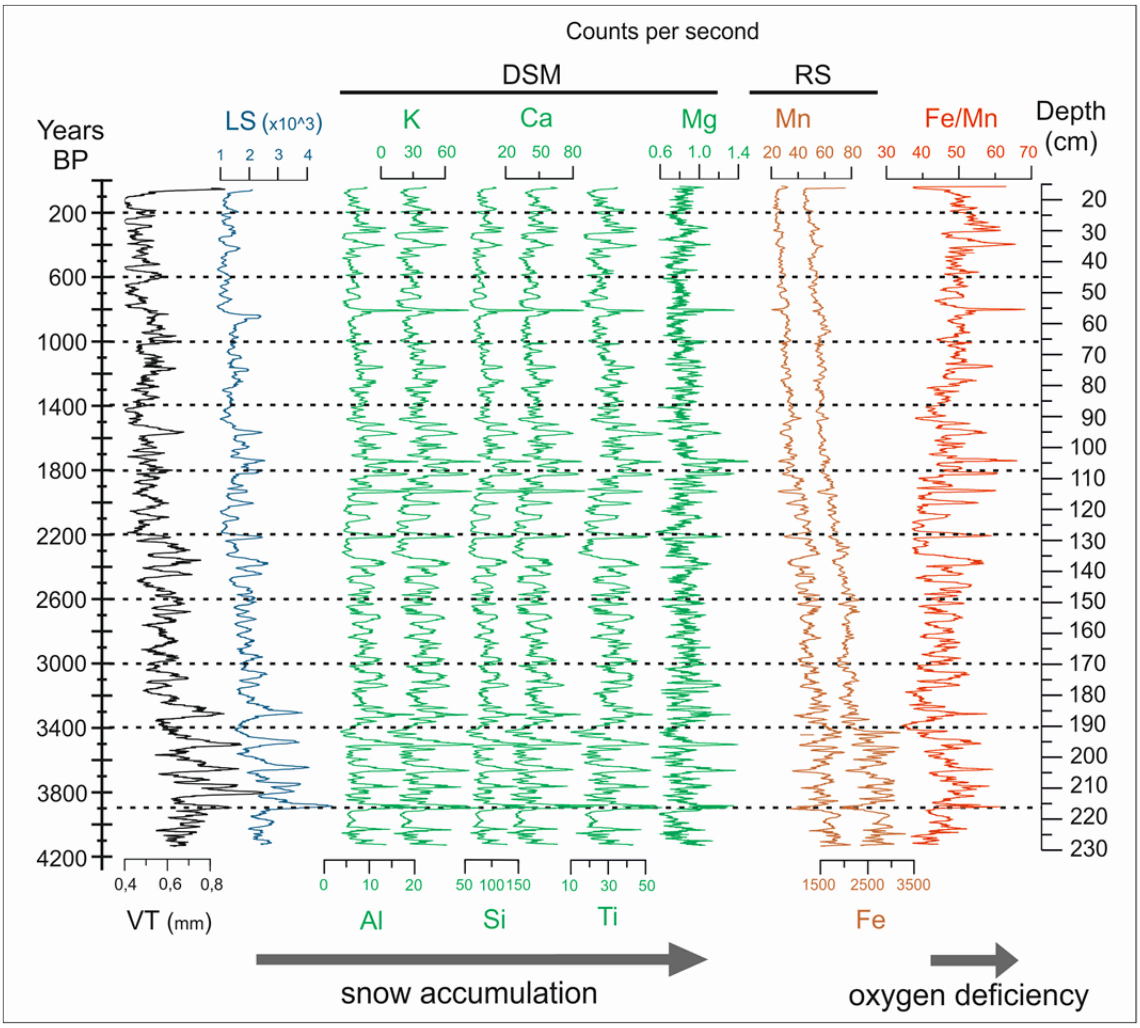

Figure 7. Displayed from the left to right are: varve thickness (VT), light sum (LS) and elemental data divided in detrital silicate mineral-association (DSM), redox sensitive association (RS) and Fe/Mn ratio with 21-year moving average from core KAL-1. At the bottom of the figure environmental interpretations are provided.

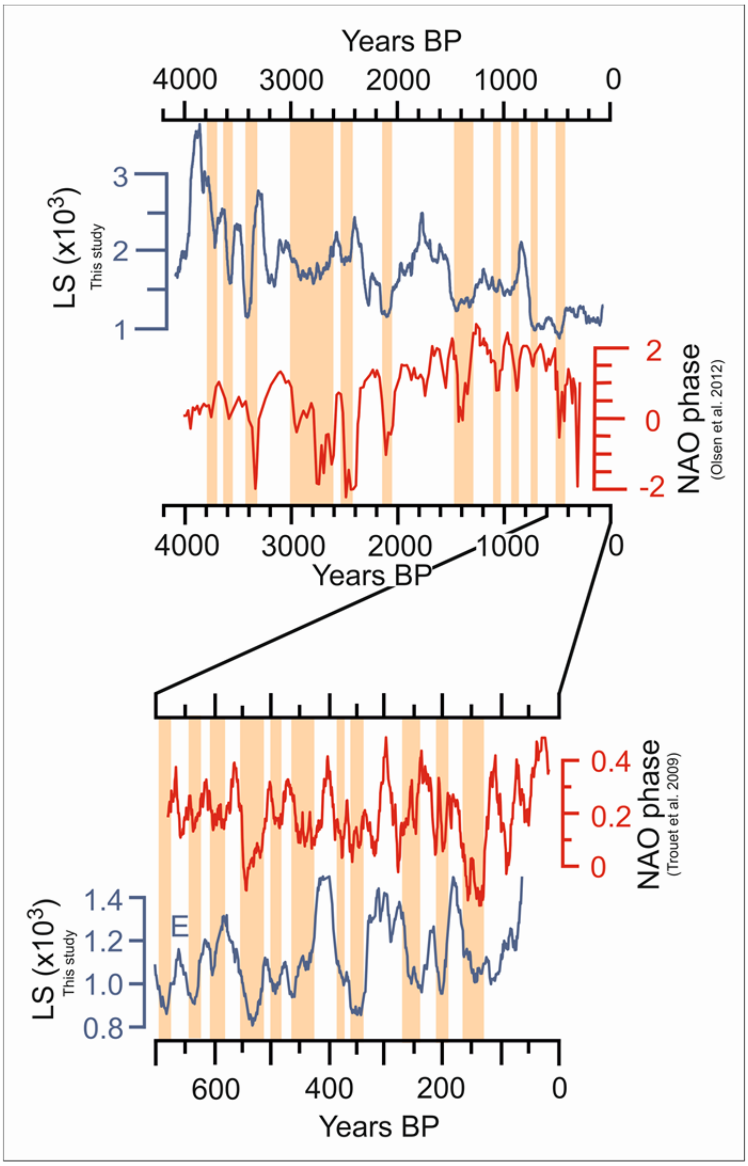

Figure 8. Comparison of Lake Kalliojärvi LS data and the NAO phases reconstructed by Olsen et al (2012) and Trouet et al (2009). The shadings highlight the periods of decreased NAO phase.

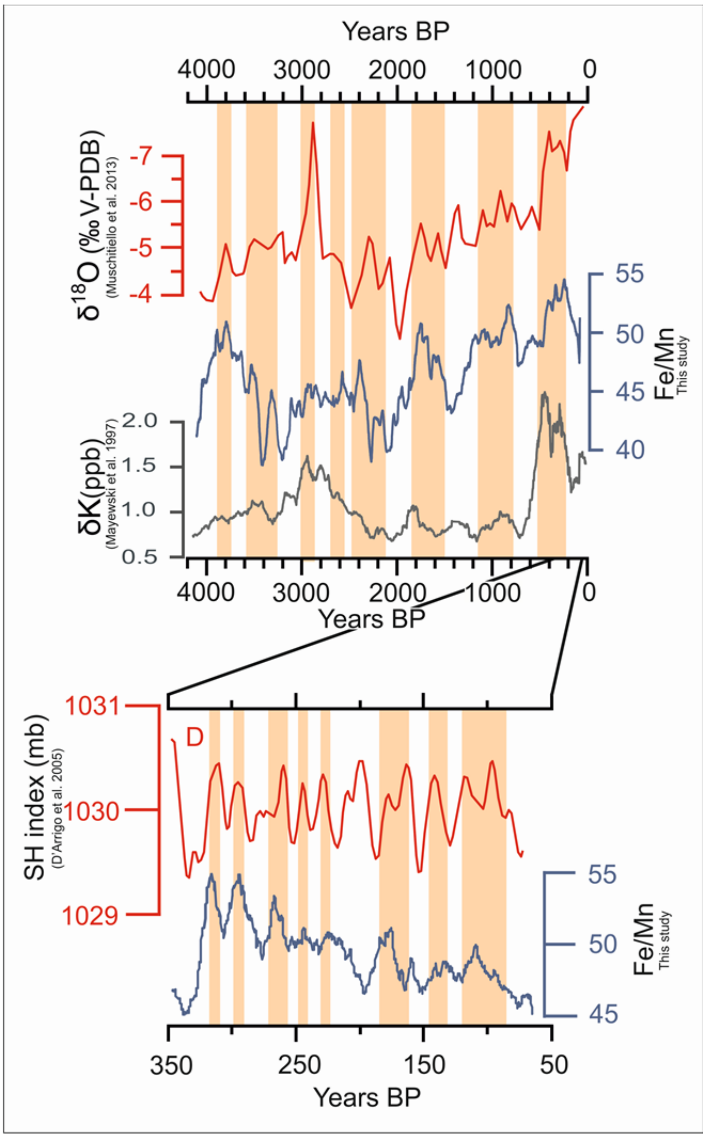

Figure 9. Comparison of Lake Kalliojärvi data and reconstructed Siberian High (SH); $\delta^{18}O$ from Bjärsträsk, Sweden (Muschitiello et al. 2013), Fe/Mn ratio from Lake Kalliojärvi, δK from the GISP2 Greenland ice core (Mayewski et al., 1997), and SH pressure index reconstruction (D'Arrigo et al, 2005). The shadings highlight the periods of strengthened SH.