A 3000-year palaeoenvironmental record from annually laminated sediment of Lake Korttajärvi, central Finland

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High-resolution physical analyses (varve thickness and relative X-ray density) were conducted on a 3000-year varved sediment sequence in Lake Korttajärvi, central Finland. Climate and the local environment strongly influence the properties of the lake sediments, and, through a combination of physical proxies, severe and favourable climate periods and anthropogenic effects on sedimentation with an annual to decadal resolution could be detected. We observed previously identified historical climate periods in the Lake Korttajärvi varve record. The Medieval Climate Anomaly (often termed the Medieval Warm Period) of AD 980–1250, which is characterized by highly organic sediment and a minor minerogenic flux during mild winters, started and terminated abruptly, but also included a short (30-year) colder period lasting between AD 1115 and AD 1145. The Little Ice Age, however, was not clear in our record, although there were two minor cooling periods in AD 1580–1630 and AD 1650–1710. Natural variability in the sediment record was disrupted by increased human impact in the catchment area at AD 1720. There is a distinct positive anomaly in mineral matter accumulation between 907 and 875 BC, which indicates more severe climate conditions. This period exists contemporary with a cold event, recorded worldwide, *c*. 2800 years ago.

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To explain the observed 20th century global warming trend and to predict future climate change it is important to understand natural climate variability. Past climate changes are also used to test the performance of climate models. Instrumental climate data, however, have only been collected for a few centuries (in central Finland since 1881, Ojansuu & Henttonen 1983) and there is a need to extend our knowledge of past climate changes by using documentary records and geological archives. Annually laminated (varved) lake sediments offer an accurate high-resolution tool to study the past environment.

A varve is defined as a set of lamina deposited during one year (Sturm 1979; Renberg 1981a; O'Sullivan 1983; Saarnisto 1986). Couplets of light and dark lamina, which may also include several internal coloured layers, are composed of mineral, organic or chemically precipitated material. Diatoms may also be important elements in the formation of visible varves (Saarnisto *et al.* 1977; Simola 1977) as their production fluctuates seasonally.

The sediments studied are located in the topographically highly variable Precambrian granitic terrain of the Finnish Lake District, which contains numerous lake basins and is conducive to the formation and preservation of annually laminated sediments. The first lakes in Finland found to contain annually laminated sediments were meromictic deep bedrock basins, kettle-hole lakes or large lake basins with a high rate of mineral matter accumulation (Kukkonen & Tynni 1970; Saarnisto 1986; Ojala *et al.* 2000). Lake Korttajärvi (Fig. 1) is a different type of lake basin. It contains annually laminated sediments and has the following typical characteristics: (1) a sheltered location, i.e. high relief bedrock outcrops, (2) a drainage area of fine-grained matter (arable land), (3) at least one large inlet and outlet, and (4) a suitable lake basin morphometry, as described by Saarnisto (1986) and Ojala *et al.* (2000). Seasonal anoxia or permanent oxygen deficiency in the deepest basin of a lake reduces the bottom fauna and the laminated structure is preserved due to the lack of bioturbation and bottom currents (Saarnisto 1986; Petterson *et al.* 1993).

The distinct seasons of the contemporary Finnish climate favour an annual rhythm of lake sediment accumulation. For example, lakes in central Finland are frozen for *c*. 5 months each year, which means that the sediment properties mirror the regional climate as well as local catchment conditions. Atmospheric circulation patterns have a strong impact on the Finnish climate, in particular the North Atlantic Oscillation (NAO), which is an important feature of winter climate in Europe (Hurrel 1995). A high positive NAO index indicates a strong pressure difference between the Azores and Iceland, which causes warm and relatively moist westerly air masses to move over Fennoscandia. The main effect of the NAO in Finland is seen to cause variable winter temperatures, while temperatures in the summer, spring and autumn are less affected (Fig. 2).

Human disturbance on the Finnish lake ecosystem is a relatively recent event when compared to the more westerly and more southerly parts of Europe, where

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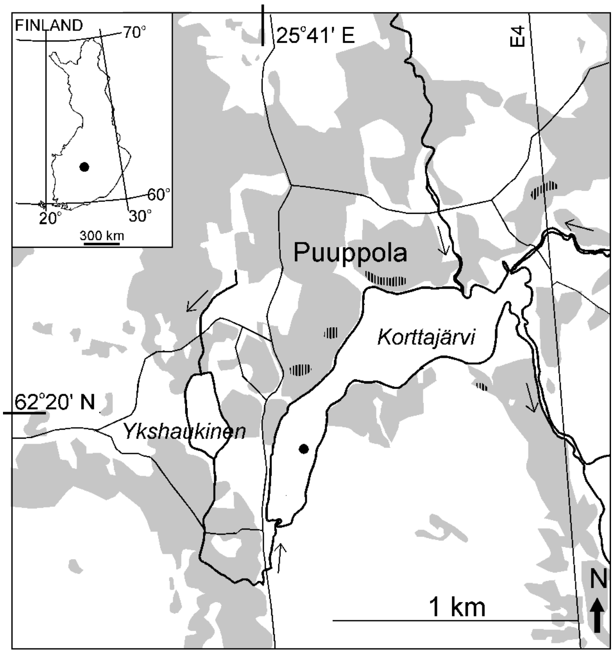

Fig. 1. Location of Lake Korttajärvi. Grey areas indicate arable land and Stone Age sites are striped. Black lines are the main roads and the black dot is the coring site.

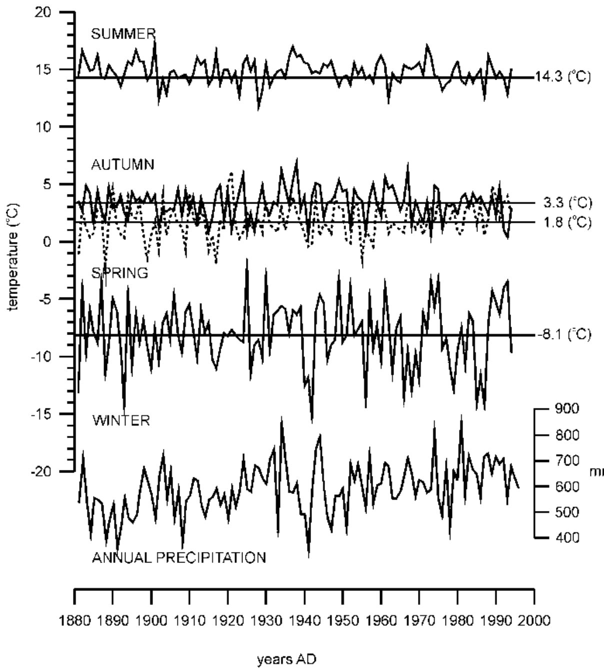

Fig. 2. Seasonal temperature from the meteorological data at Lake Korttajärvi area for the years AD 1881–1993 (Ojansuu & Henttonen 1983). Summer (average June, July, August), autumn (average September, October, November), spring (the dotted line) (average March, April, May) and winter (average December, January, February). A line marks the average temperature of each season. Annual precipitation is also included.

agricultural activities began *c.* 3500 and 2750 years ago, respectively (Zolitschka & Negendank 1997; Allen *et al.* 2002; Berglund 2003). In the Lake Korttajärvi area, land use was not intense until the late 16th century (T. Alenius unpublished), although some archaeological finds dated to the Stone Age are located near the shore. Thus varves formed prior to and during the Middle Ages, which are one focus of the present study, are likely to contain information about natural environmental changes.

Current developments in digital analysis techniques have enabled the accurate documentation of long varve sequences (Saarinen & Petterson 2001; Ojala & Francus 2002). It is now possible to interpret long varve records with one year or seasonal resolution. Variation in the relative X-ray density describes the structure of the sediment and provides information about the sedimentary environment. Varve thickness indicates the rate of sediment accumulation, and magnetic measurements have been used to provide information on the nature of the accumulating mineral particles (e.g. Snowball *et al.* 1999, 2002).

Here we present the results of the analysis of the Lake Korttajärvi varved sediment sequence. The sequence analysed covers the well-established climate development of the last 3000 years, which includes the Little Ice Age and the Medieval Warm Period and extends to the Migration Period, the time of the Roman Empire and the widely recognized cold period *c.* 2800 years ago (Denton & Karlén 1973; van Geel *et al.* 1996; van Geel & Renssen 1998). The entire Korttajärvi sediment sequence covers nearly 10 000 years and will be described elsewhere (Ojala & Tiljander in prep.).

Study site

Lake Korttajärvi (62°20′N, 25°41′E) has a surface area of 0.45 km^2 and is situated in central Finland about 10 km north of the city of Jyväskylä, 94.4 m above sea level (Fig. 1). It is the central lake of the larger Tourujoki watercourse (Palomäki 1996). The mean annual discharge is 2.1 $m^3\,s^{-1}$ and the residence time is 0.3 months. The outlet of the lake runs into Lake Alvajärvi, Lake Palokkajärvi and finally into Lake Päijänne. According to the data of Saarnisto (1971), Lake Korttajärvi was isolated from the Ancient Lake Päijänne 6100 ^{14}C years BP (6800 cal. years BP), when Lake Päijänne cut a new outlet to the south due to isostatic uplift, and the water level dropped by several metres. The drainage basin of Lake Korttajärvi is covered by the easily eroded fine-grained (silt) bottom sediments of Ancient Lake Päijänne and by glacial till. The bedrock of the area is composed of porphyritic granite.

Lake Korttajärvi consists of two basins that are separated by a shallow (1.2 m) threshold. The southern basin (where the sediment cores were recovered) is 12.5 m deep and the northern basin is 10.2 m deep. The southern basin has one inlet and the northern basin has two. The inlet in the northern basin has an insignificant effect on water circulation and sedimentation in the southern basin. The only outlet is in the eastern corner of the northern basin. Although the sediments of both basins are laminated, the lamination structures appear better preserved in the southern basin, which was therefore selected for further analysis. The sequence is continuously laminated throughout the post-isolation sediment profile (11.6 m).

Archaeological surveys have revealed five Stone Age dwelling sites around Lake Korttajärvi (T. Sepänmaa, pers. comm. 1998). Quartz tools have been found from all sites on sandy-silty soils near the shoreline (Fig. 1). The time period of prehistoric human occupation, however, is unknown.

According to climate statistics from the Atlas of Finland (Alalammi 1987), which cover the period from 1931 to 1960, the mean annual air temperature in Jyväskylä was +3°C and the mean temperature in July, the warmest month, was +16°C. Temperature fell below 0°C in November and rose above 0°C in early April. Average mean temperatures remained below −5°C from November to March, the coldest months being January and February with a mean temperature of −9°C. Figure 2 shows that the mean winter temperatures in the area around Lake Korttajärvi have varied ±8°C during the observed period since AD 1881 (Ojansuu & Henttonen 1983), while mean summer temperatures have been more stable (below ±3°C). The beginning of the seasonal snow cover broadly follows the date of the −3.5°C mean daily temperature, which in the Lake Korttajärvi area is 11 November, and the snow cover disappears between 22 and 28 April. During the time period from 1960/61 to 1992/93 the mean annual precipitation was over 650 mm, of which *c.* 260 mm fell as snow (Alalammi 1987). Between AD 1951 and 1970, the surfaces of lakes in the Jyväskylä area froze by 20 November and the ice began to break up around 10 May (Karlsson 1986). In central Finland, 85% of the annual maximum flood occurs in spring and the amount of water derived from snow at the beginning of the spring melt is 6–10 times greater than the total precipitation during the entire snowmelt period (Kuusisto 1984).

Anthropogenic impacts are visible in the present-day water quality. Since the early 20th century, wastewater from the drainage area was directed into the watercourse of Lake Korttajärvi. According to local people, the lake water was quite polluted in the mid-20th century. Diatoms indicate that the lake water was acidic until the 19th century, after which the diatom assemblages indicate increasing eutrophication (Grönlund & Vuorela 2000). The high nutrient input made the lake eutrophic. However, when the wastewater loading was reduced, the phosphorus content declined to half the peak values and has been stable since AD 1980 (Palomäki 1996). Lake Korttajärvi is currently a eutrophic lake with a total phosphorus concentration of >30 μg/l and a mean bottom-water oxygen concentration (in the late 1980s) of ~4 mg/l (Palomäki 1996).

Methods

Coring and subsampling

Samples were collected for pollen, diatom and loss-on-ignition (LOI) analyses in 1997, with the chronology then based on the correlation of palaeomagnetic secular variation features (Saarinen 1999). New sediment cores were collected for more detailed varve counting and physical analysis in 1999. A Livingstone-type piston corer was used to recover the top 2 m of the sediment (8 parallel cores were taken in January 1999) and a PP piston corer (Putkinen & Saarelainen 1998) was used to obtain a 9 m long core in April 1999. The long core was cut into 1.5 to 2.0 m sections for transportation and storage in cold room at +4°C. An *in situ* freezing system was used to recover the uppermost sediment sequence in 1997 and 1999 (Wright 1980; Renberg 1981b; Saarnisto 1986).

Varve counting

The varve chronology is based on two cores, 99e (1.79 m) and HU99 (8.95 m). Core 99h (at a depth of 0.90–2.20 m from the sediment surface) was only used for varve counting at the first cut point of core HU99. The varves in the top of the sediment were counted from a photographed freeze core. The cores 99e, 99h and HU99 were cut into $1 \times 1 \times 12$ cm subsamples and embedded in epoxy according to a method described by Lamoureux (1994) and Tiljander *et al.* (2002). Embedded samples were then cut and polished into 2 mm thin slices ($0.2 \times 1 \times 12$ cm) for X-radiography. The X-ray negatives were scanned to produce images (TIF format) that were examined using a semi-automatic counting program, DendroScan (Varem-Sanders & Campbell 1996), originally developed for tree-ring width and density measurements. The varve counts made by the computer program were confirmed by visually checking each sample under a stereomicroscope. For further details of sample treatment, see Tiljander *et al.* (2002).

Laminations in the sediment were interpreted as annual, based on photographs taken from the frozen core samples at years 1997 and 1999 (Fig. 3). To prove the annual character of the sediment, a scanning electron microscope (SEM) technique (low-vacuum Jeol JSM-5900) was used. Embedded epoxy samples coated with carbon were studied with a backscatter electron image mode (BSEI). The varve structure is

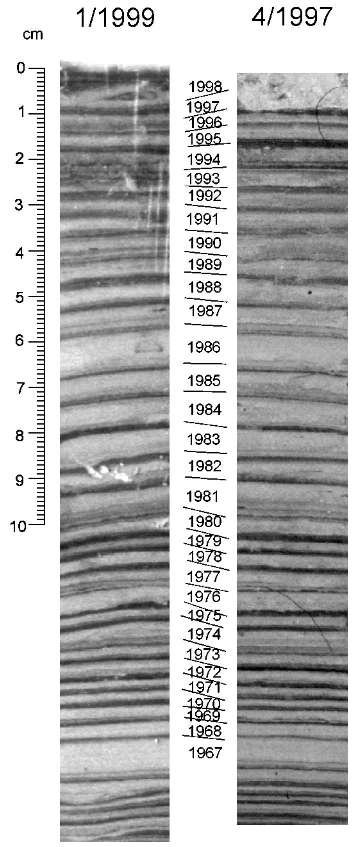

Fig. 3. Photographs from the frozen core samples taken in January 1999 and in April 1997.

clear (Fig. 4) and shows graded bedding of the mineral grains. It is perfectly reasonable to assume that the grading structure originates from the annual rhythm of sedimentation. Only in spring is the river discharge strong enough to transport a large amount of mineral particles (Tikkanen 1990), which are deposited in the lake basin. River discharge is lowest during the period of winter ice cover, when the finest grained mineral particles and less dense organic material can accumulate.

Varves were counted from separate cores by the first author. Counting was carried out twice from core 99e and once from core HU99 and one more time to compare the cores. There were some sections where the varve structure was unclear in separate cores, mainly due to the subsampling or coring. However, counting was achieved by comparing replicate cores to each other. If repeated varve counts were different an error was estimated. For example, if there was an uncertainty about the presence of a varve boundary, i.e. it was considered that there might be two thin varves instead of one thick varve, an error of +1 year was noted.

Volume magnetic susceptibility measurements were made on unopened cores at a resolution of 2 cm (Bartington Instruments MS2C sensor) and immediately after opening at a resolution of 5 mm (MS2E1 sensor). Magnetic susceptibility measurements and visual inspection of sediment stratigraphy were used to correlate core A97 (taken in 1997) to core HU99. The susceptibility of discrete subsamples taken from core A97 was measured with separate equipment (KLY-2, Kappabridge) at 1.5 cm intervals. As shown in Fig. 5, the sediment accumulation rate varied between cores.

Results

Varve formation in Lake Korttajärvi

The annual sediment accumulation rate in Lake Korttajärvi varies between 0.5 and 2.0 mm. The basic sediment structure in Lake Korttajärvi is similar to the clastic-biogenic type defined by Ojala *et al.* (2000), where varves are composed of two major lamina of mineral matter (mostly deposited in spring and early summer) and organic matter (deposited during the

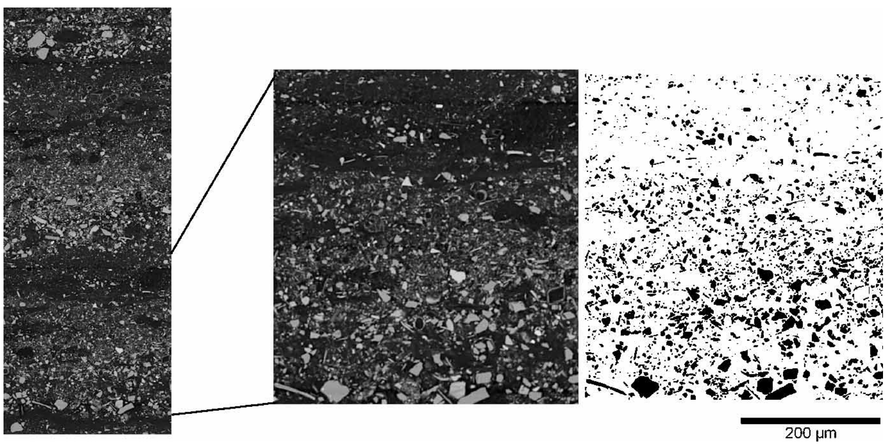

Fig. 4. Two and half varves (left) as backscattered scanning electron microscope image (BSEI) from an embedded sample and a detailed image of single varve year (centre), converted into a binary image (right) illustrating the graded bedded structure of black mineral grains (*c.* AD 1300; core 99e).

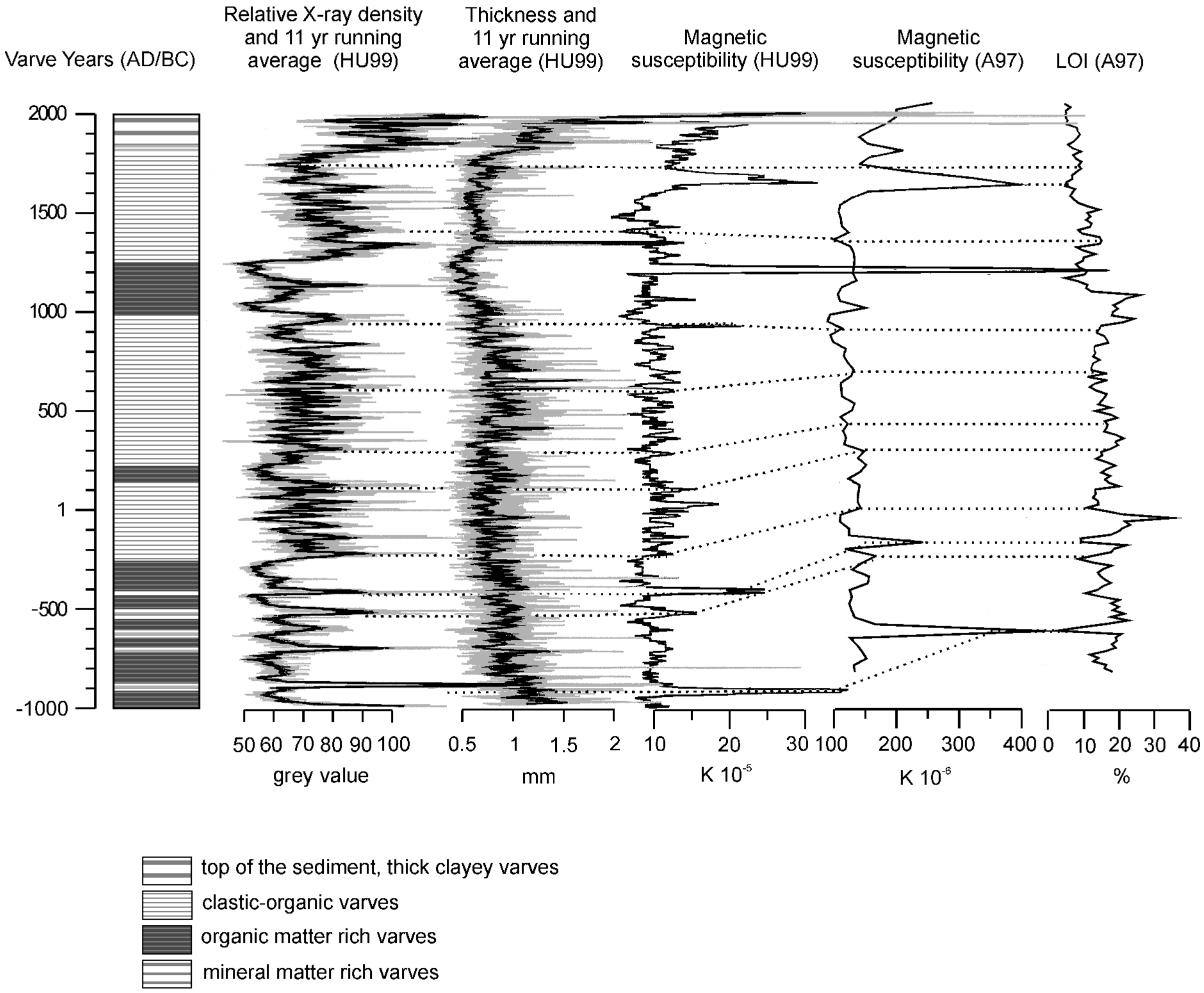

Fig. 5. Description of the sediment sequence. Two parallel cores are correlated according to magnetic susceptibility measurements. Relative X-ray density variation, varve thickness, magnetic susceptibility and loss-on ignition (LOI) variation within the past 3000 years are presented. High X-ray density corresponds to high amount of mineral matter (light grey value tints in X-ray film) and low X-ray density corresponds to dark grey values caused by a higher proportion of organic matter.

remaining seasons). The spring diatom bloom, which occurs almost immediately after the snowmelt, is emphasized in the mineral-rich layer (Saarnisto *et al.* 1977; Simola 1977). In addition, the Lake Korttajärvi sediment sequence has some sections consisting almost exclusively of either mineral matter or organic matter.

The accumulation of the mineral lamina is most likely a short-term event and the thickness of the mineral layer is directly related to the duration and strength of the spring flood. In early spring, the soil is not yet stabilized by a thick grass cover and it is susceptible to erosive forces. The internal varve structure shows graded bedding (Fig. 4), where the grain size at the onset of the spring varve layer is *c.* 40 μm. The grain size decreases gradually to <10 μm during the winter layer. In mild winters the snow cover remains thin, but the ground is often frozen to prevent erosion. Mild winters, with frequent snow thaws, lead to weak spring floods that cause only minor mineral matter influx into the lake system and the varves formed lack a distinctly graded bedding structure.

The thickness of the organic lamina is the sum of autochthonous production within the lake and the amount of allochthonous material and is related to the primary production during the open water season. The layer above the mineral matter is defined as organic, because of the less dense structure in X-ray images and low grey-scale values. A thick organic lamina probably indicates a warm summer and a relatively long growing season. The end of the varve year, i.e. the deposition under the ice cover in sheltered conditions, is marked by the sedimentation of a dark, almost black, layer consisting of very fine-grained organic matter.

Additionally, heavy rainfall events in any open water

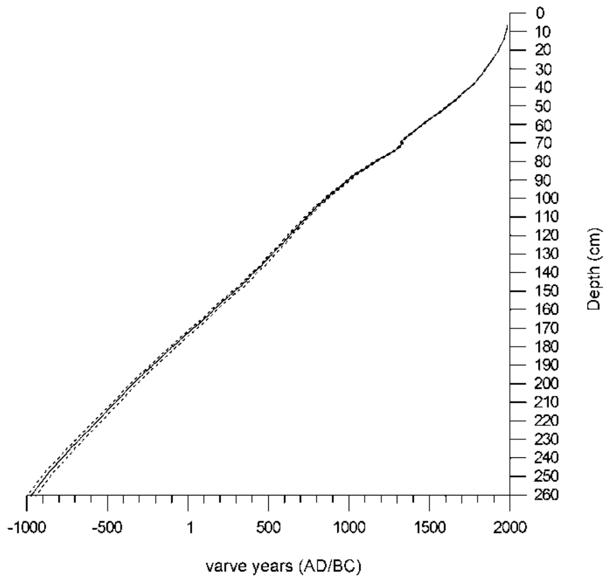

Fig. 6. Time-depth diagram including varve chronology error estimates.

season may cause pulses of mineral matter, which can cause irregularities in the internal structure of varves. Under microscopic examination it is possible to distinguish irregularities in internal structures from true varves.

The above-mentioned factors, the amounts of inorganic and organic matter, form the basis of the climate interpretations. Periods rich in organic matter indicate favourable climate conditions, when less snow accumulates in winter by diminished precipitation and/or increased thawing, causing weaker spring flow and formation of a thin mineral layer. In addition, a long growing season thickens the organic matter. More severe climate conditions occur with higher winter precipitation, a longer cold period and rapid melting at spring, shown as thicker mineral matter within a varve. However, it is difficult to make climatic interpretations at the annual time scale, but short-term changes (averaged over a few years) could be estimated.

Chronology

Comparison of the frozen core sample with the other cores enabled determination of the first year of each core. The first varve of the core HU99 corresponds to the year AD 1985, and the top 2.6 m of sediment from this core cover the last 3000 years. Core 99e covers the years AD 1988–357 BC. Error estimation is based on the deviation of the repeated counts (Fig. 6, Table 1). In this 3000-year record the error is $\pm$ 0.8–1.0%, which is in the same range (1–2%) as in other high-resolution varve studies (Ojala & Saarnisto 1999; Ojala & Saarinen 2002; Snowball *et al.* 1999, 2002; Petterson 1999) and Greenland ice core studies covering the Holocene (Alley 2000).

Table 1. Cumulative error estimates in 500 year periods.

Date AD/BC	Error estimate (−)	Error estimate (+)
AD 1500	6	5
AD 1000	12	11
AD 500	21	13
1 AD/BC	23	16
500 BC	26	18
1000 BC	29	26

Characteristics of the sediment sequence and of special time periods

Varve thickness in core HU99 varies between 0.2 and 6.7 mm (with the exception of the 18.9 mm varve in AD 1326 (+5/−7)). Average varve thickness (Fig. 5) is *c.* 1 mm during the first millennium BC. Between 1000 and 600 BC the average varve thickness is 1.01 mm, and between 600 BC and AD 900 slightly less (0.84 mm). The thinnest varves accumulated from AD 900–1800 (average 0.68 mm), and during the last 200 years the average varve thickness has been 1.60 mm. This recent increase in thickness is due to the clay-rich varves caused by intensive cultivation in the late 20th century. It must also be considered that the uppermost sediments are less consolidated than the underlying sediments, which can lead to apparently thicker upper varves.

Even though the sequence is varved throughout, there are differences in the nature of the deposited material (Fig. 5). In the lowest sediment section considered here, before 220 BC, there are two alternating sediment types: sequences of organic (average grey value <65) and sequences of mineral-rich varves (grey value distinctly >65). The periods are short and distinct, i.e. the changes in the sediment properties are abrupt and easily recognized as changes in the colour of the fresh sediment surface (Fig. 7) and the relative X-ray density curve (Fig. 5). The length of the organic-rich periods varies between 44 and 72 years and 148 years (Table 2), with mineral-rich varves in between covering 27–38 year periods. One of these periods is the most dominant mineral matter rich period that occurred between 907 and 875 BC. The sediment section from 250 BC to AD 1250 is more regular, possessing two longer organic-rich periods from AD 140–220 and AD 980–1250. Between AD 1250 and 1750 a higher relative X-ray density reflects increased mineral accumulation and there were four periods when mineral matter rich varves accumulated (Table 2). During two periods, AD 1580–1630 and AD 1650–1710, the varve thickness also increased. From the mid-18th century the amount of mineral material accumulation accelerated markedly towards the modern times, which is also reflected by the higher values of magnetic susceptibility.

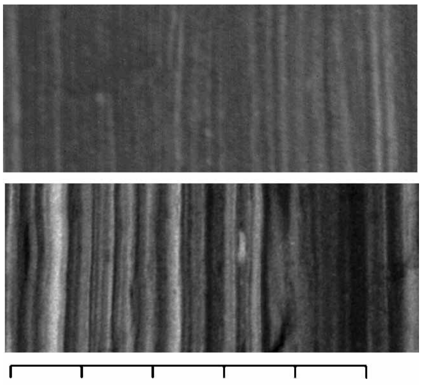

Fig. 7. A detailed X-ray radiography (core HU99) of varves with a relatively high proportion of organic matter (up) AD 1235–1209 and high amount of mineral matter (down) 721–706 BC.

Discussion and conclusions

Palaeoclimate

Several global and hemispheric atmospheric temperature reconstructions have been made from multi-proxy data. Mann *et al.* (1999) based a northern hemisphere temperature reconstruction of the last millennium on a combination of tree-ring density and widths, oxygen isotope and ice accumulation data. Jones *et al.* (1998) also underlined the multi-proxy approach, using available instrumental temperature data, borehole temperatures, historical documents, tree-rings (density and width), corals (calcification, isotopes), ice cores (isotopes, melt layers) and palaeolimnology (pollen and diatoms).

In the case of Lake Korttajärvi it is a demanding task to calibrate the physical varve data we have collected against meteorological data, because human impacts have distorted the natural signal to varying extents during the past 280 years and the meteorological data in the Jyväskylä area are only available since 1881 (Ojansuu & Henttonen 1983; Fig. 2). The relative X-ray density provides a general picture of the sediment composition, and is therefore used in the following climate interpretation.

Table 2. Special time periods of the characteristic varve structures.

AD 1650–1710	60 yr	Mineral matter
AD 1580–1630	50 yr	Mineral matter
AD 1380–1420	40 yr	Mineral matter
AD 1302–1338	36 yr	Mineral matter
AD 980–1250	270 yr	Organic matter
AD 1115–1145	30 yr	Mineral matter
AD 140–220	80 yr	Organic matter
408–260 BC	148 yr	Organic matter
434–409 BC	26 yr	Mineral matter
505–435 BC	70 yr	Organic matter
541–506 BC	36 yr	Mineral matter
586–542 BC	44 yr	Organic matter
623–587 BC	37 yr	Mineral matter
688–624 BC	64 yr	Organic matter
725–689 BC	37 yr	Mineral matter
874–726 BC	148 yr	Organic matter
907–875 BC	32 yr	Mineral matter
980–908 BC	72 yr	Organic matter

Interpretation of the Lake Korttajärvi record

First millennium BC. – According to relative pollen analysis of the Lake Korttajärvi sediment sequence (Grönlund & Vuorela 2000) the lake was surrounded by a spruce forest at the beginning of the last millennium. During the period 970–220 BC the amount of spruce (%) and deciduous tree pollen decreases while herb pollen increases, indicating a lighter and more open landscape. The short-term increase in Alnus also indicates early forest clearing in the area. The first cereal pollen (Hordeum) appears around 200 BC.

The first two-thirds of the 1st millennium BC are dominated by cyclical changes in sedimentation. Mineral and organic-rich periods alternate quite regularly. The length of these periods has been determined from the relative X-ray density data. The organic-rich periods (Table 2) lasted 148, 70, 44, 64, 148 and 72 years. These periods could reflect climate variation recorded by Schlesinger & Ramankutty (1994) in the North Atlantic region. These authors observed temperature oscillations with a period of 65–70 years, the most probable cause being an internal oscillation of the atmospheric-ocean system.

The most intensive period of catchment erosion within the past 3000 years, from 907–875 BC, started abruptly with the deposition of 21 thick clastic varves, which was followed by 12 thick varves rich in organic matter. This 21-year period is characterized by higher mineral matter accumulation than the 500 years before and after this event (Fig. 8). This period around *c.* 900 BC could indicate the same abrupt climate change as described by van Geel *et al.* (1996) and van Geel & Renssen (1998), when a sudden rise in the ^{14}C content of the atmosphere *c.* 850–760 BC coincided with wetter and cooler conditions in The Netherlands and also around the world. They hypothesize that the climate change was linked to low solar activity. According to Denton & Karlén (1973), the higher ^{14}C activity (low solar magnetic field) coincides with alpine glacier expansions at 2800 cal. yr BP.

Peat bog investigations in southern Finland show that between 650 and 450 BC there was a high rate of carbon accumulation representing increased humidity (Mäkilä 2001). Slightly humified peat indicates a wet and cool climate. By combining several peat records the highest carbon accumulation period was earlier, *c.* 1000–800 BC (Mäkilä 1997 and pers. comm. 2001). A lake-level study from a small lake in southern Finland also shows

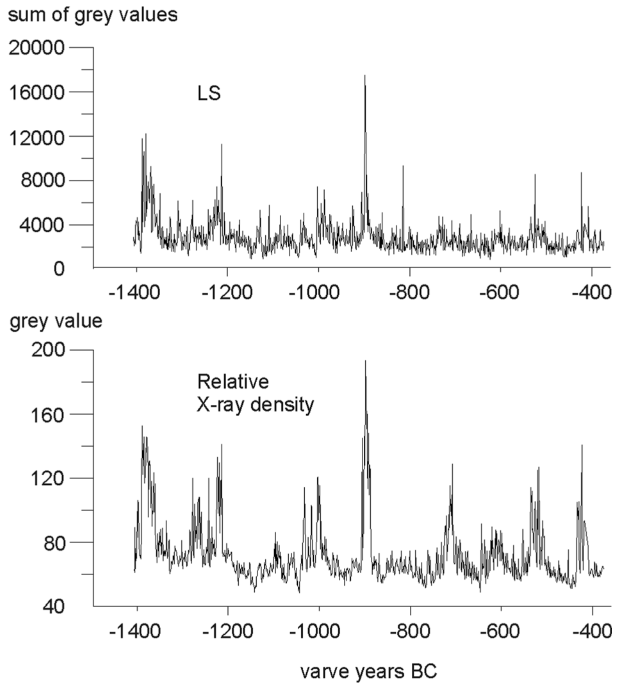

Fig. 8. Relative X-ray density and the sum of grey values within a varve (LS) representing the amount of mineral matter during the time period 1407–375 BC.

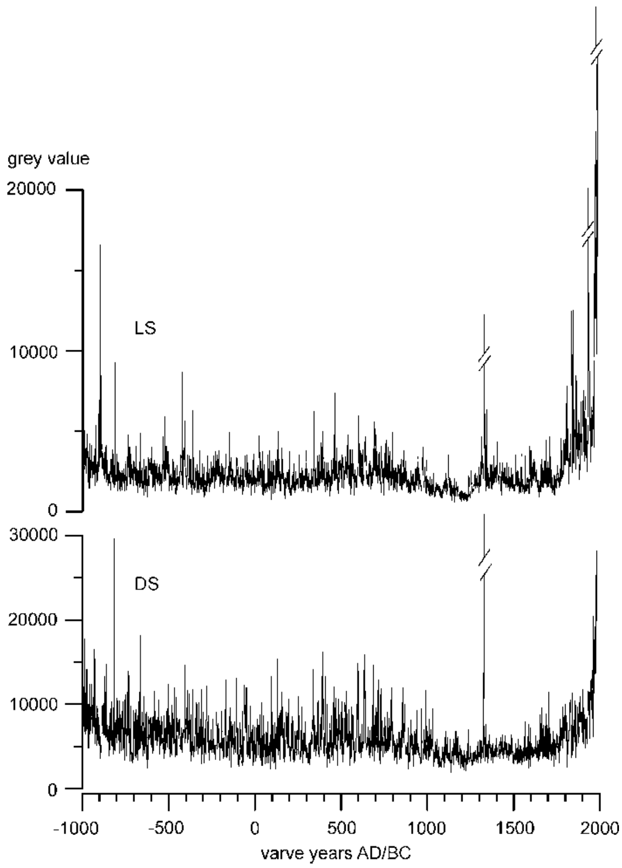

Fig. 9. Amount of mineral and organic matter deposited during 3000 years. LS (light sum) is the sum of grey values and describes the amount of mineral matter. DS (dark sum) = $LS_{max} - LS$ and describes the amount of organic matter.

that the water level was higher during that time (Sarmaja-Korjonen 2001).

AD 1–400: The Roman period. – During the first centuries of the first millennium AD, there is an 80 year long period (AD 140–220) rich in organic matter. The properties of the sediment during this period are similar to the Medieval period, with a high organic matter content, which we interpret as climatically genial conditions in the Lake Korttajärvi area (minor amount of heavy spring floods indicating milder winters). According to Briffa (2000), the tree-ring record of northern Sweden shows a genial climate period during the first two centuries of the first millennium.

AD 400–850: Migration period and early Middle Ages. – No significant changes are recorded by the varves in the Lake Korttajärvi during this period. The amount of mineral and organic matter (i.e. sedimentation rate) remains stable (Fig. 9).

AD 850–1500: The Middle Ages. – Human activity gradually increases near the lake. The forests in the vicinity of the lake are still spruce dominated, but small-scale slash-and-burn cultivation was practised occasionally. The first rye (*Secale*) pollen appears in the late 8th century (T. Alenius, unpublished).

An organic rich period from AD 980 to 1250 in the Lake Korttajärvi record is chronologically comparable with the well-known 'Medieval Warm Period' (e.g. Lamb 1965; Grove & Switsur 1994; Broecker 2001). The sediment structure changes, less mineral material accumulates on the lake bottom than at any other time in the 3000 years sequence analysed and the sediment is quite organic rich (LOI ~20%). Thus, the winter snow cover must have been negligible, if it existed at all, and spring floods must have been of considerably lower magnitude than during the instrumental period (since AD 1881). According to the scenarios presented by Solantie & Drebs (2001), a +2°C increase in winter temperature would decrease the amount of snow in southern Finland significantly. Under such conditions, winter snow accumulation and intense spring floods would be rare events.

The relative lack of mineral matter accumulation and high proportion of organic material between AD 950 and 1200 was also noticed in two varved lakes in eastern Finland (Saarinen *et al.* 2001) as well as in varves of Lake Nautajärvi in central Finland *c.* AD 1000–1200 (Ojala 2001). Common to all sites is that the warm period lasted more than 150 years.

There was a reasonably warm period in Greenland at the end of the 10th century when the Vikings settled there and the settlements existed until the onset of the cold 14th century (Dansgaard *et al.* 1975). The ‘northern average’ tree-ring record (Briffa 2000) also shows a relatively warm period around AD 1000–1200, and Growley & Lowery (2000) found evidence of three short warming periods during Medieval times (AD 1010–1040, AD 1070–1105 and AD 1155–1190).

According to Hughes & Diaz (1994) regional warm episodes were asynchronous and the Medieval Climate Anomaly cannot be considered as a synchronous global phenomenon, but this hypothesis is still not proved (Broecker 2001; Grove & Switsur 1994). There is glacial evidence of a warmer period in AD 900–1250 interrupted by a minor ice re-advance between about AD 1050 and 1150 (Grove & Switsur 1994). According to the Lake Korttajärvi varve record there is a short period, AD 1115–1145, with increased mineral matter accumulation, indicating more severe winters. In the Fennoscandian tree-ring record (Briffa *et al.* 1990), the largest 50-year cooling trend in the 1400-year long record (-1.78°C) occurred between AD 1090 and 1139 and the coldest 20-year mean occurred between AD 1127 and 1146.

The existence of the Medieval Climate Anomaly is widely accepted, although Bradley (2000) doubts that it was as warm as the last few decades of the 20th century. Also some records indicate that the Medieval temperatures were less than or comparable to the mid-20th century warm period (Growley 2000). A Greenland borehole record, however, implies that the Medieval period was 1°C warmer than today (Dahl-Jensen *et al.* 1998).

In the case of our study, hydrological conditions have changed the discharge at the area of Lake Korttajärvi. According to a recent detailed study (sediment structure, pollen, diatoms and phosphorus (Kauppila *et al.* in prep.) the Medieval Warm Period was a two-stage event. AD 980–1100 was a dry and warm period, which was interrupted by a cold spell (AD 1115–1145) and followed by an even drier and warm period AD 1100–1220. Even though the sedimentation in Lake Korttajärvi most likely reflects relatively long-term changes in local hydrology rather than temperature, several studies indicate a relative temperature rise during the Medieval period in Scandinavia. Evidence of warming on the Kola Peninsula (*c.* AD 1000–1300) is provided by treeline studies, which show that pine grew at least 100–140 m above the modern limit during the Medieval period, which corresponds to a (summer or annual average) temperature at least 0.8°C higher than today (Hiller *et al.* 2001). A pollen reconstruction from northern Finland suggests that the July mean temperature was *c.* 0.8°C warmer than today during the Medieval Climate Anomaly (Seppä 2001). A study based on oak barrels, which were used to pay taxes in AD 1250–1300, indicates that oak forests grew 150 km north of their present distribution in SW Finland and this latitudinal extension implies a summer temperature 1–2°C higher than today (Huldén 2001).

AD 1500–1900: Little Ice Age. – Cultivation in the Lake Korttajärvi area intensified in the mid-16th century. Hemp (*Cannabis*) is noted in pollen records since AD 1560 and continuous rye (*Secale*) cultivation since AD 1580 (T. Alenius, unpublished). The first historical record of the population in the Korttajärvi area is from the 1570s (Korpela *et al.* 1968). The population increased gradually and the main road near to the north part of the lake was constructed in the late 18th century (Alanen & Kepsu 1989).

The climate in Europe became colder after the 200–300 year Medieval Warm Period. According to several records, the Little Ice Age started around AD 1500 and lasted until the beginning of the 20th century, the coldest periods being in the 17th and 19th centuries (e.g. Bradley & Jones 1993; Jones *et al.* 1998; Fischer *et al.* 1998).

A study of glacier expansion in Swedish Lapland (Karlén & Denton 1976) indicates that the Little Ice Age in northern Scandinavia lasted five centuries; it started in AD 1500 and peaked in the 1600s, with still further fluctuations during the next centuries. Also glaciers in the Swiss Alps retreated markedly after their AD 1860 maximum and the warming was global (Broecker 2001). On the other hand, the tree-ring data from northern America indicates cold conditions in the late 19th and early 20th centuries (Bradley & Jones 1993).

The Lake Korttajärvi record also indicates a climatically more severe period in the 17th century. Two periods, AD 1580–1630 and AD 1650–1710, are marked by an increase in both sedimentation (varve thickness) and mineral matter accumulation (relative X-ray density). Also, magnetic susceptibility values are high between AD 1650 and 1710, indicating increasing mineral matter input into the lake. During the first half of the 14th century there were also two short periods when mineral-rich material accumulated, but the total varve thickness did not increase significantly.

There have been several documented crop failure years in Finland during the last 500 years (Melander & Melander 1924), but a single bad year is not revealed in the sediment record. Two short periods, AD 1542–1545 and AD 1672–1675, which are recorded as crop failure years (Melander & Melander 1924) caused by heavy rainfall, also occurred when mineral material accumulation increased in Lake Korttajärvi.

One main climate-controlling factor is the NAO. The mid-1500s to 1700s and the late 18th century were times of a negative NAO index, when westerlies were weak and cold, dry air masses spread from the east and north to Scandinavia. A positive NAO index, bringing wet and warm air masses (strong westerlies) over Scandinavia, existed in the early 16th and 18th centuries and around AD 1850 (Luterbacher *et al.* 2002). In the Lake

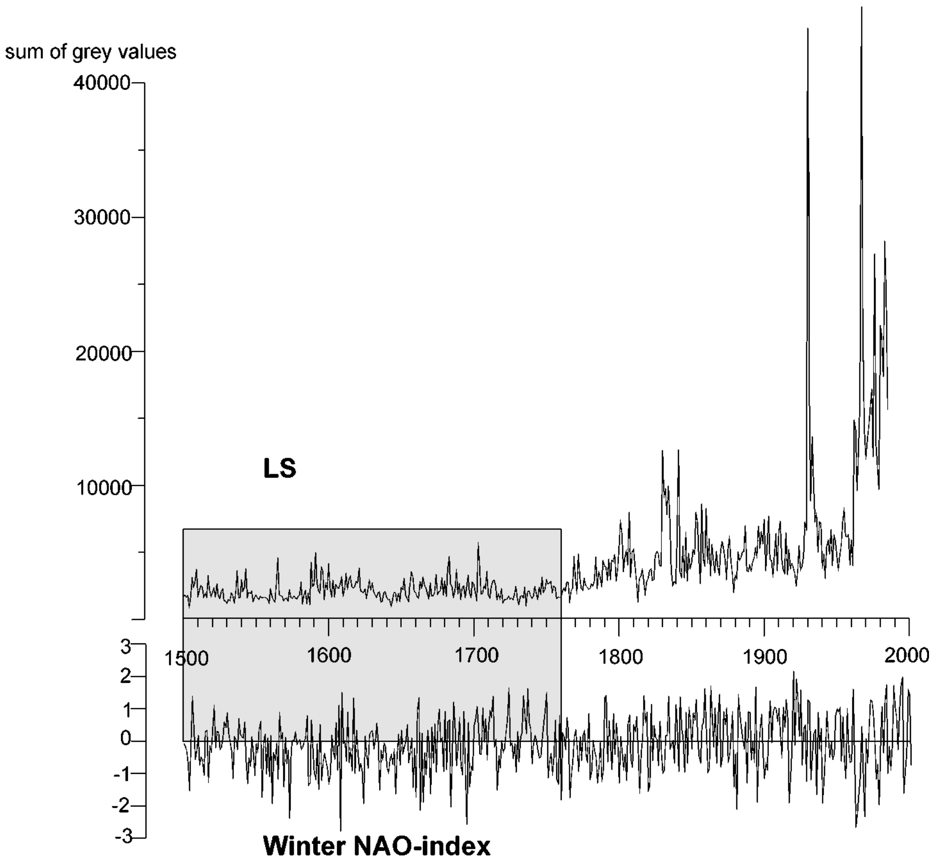

Fig. 10. Amount of mineral matter (LS) and wintertime North Atlantic Oscillation index (Luterbacher *et al.* 2002) AD 1500–2000.

Korttajärvi record the NAO impact upon the accumulation of mineral matter is distinct. The thickness variation of the mineral layer shows the same trend as the positive wintertime NAO index (Luterbacher *et al.* 2002) from AD 1500 until the mid-16th century (Fig. 10), when human impact begins to have a significant effect on the varve properties.

20th century. – In the 20th century the Lake Korttajärvi record was strongly affected by human activities. The average varve thickness is 1.2 mm from AD 1900 to 1929, 1.9 mm from AD 1930 to 1962 and 3.5 mm from AD 1963 to 1985. There are two exceptionally thick clay-silt layers caused by man. The thick layer of AD 1930 resulted from peat ditching and forest clearance (information from a local farmer in 1999) and the thick layer of AD 1967 originated due to the rebuilding of the bridge in the vicinity of the lake's southern corner (information from the Finnish Road Administration). Varves since AD 1963 towards the present time thicken because of the higher water content in the top of the sediment column. However, the gradually increasing varve thickness during the whole 20th century probably originates from the accelerating agricultural use of the area around the lake.

Summary and conclusions

The sediment record from Lake Korttajärvi shows clearly alternating mineral and organic-rich periods over the past 3000 years. The formation of highly organic periods lasting several decades requires long favourable climatic conditions and periods when more mineral material accumulated indicates more severe winter conditions. The periodical alternation is strongest between 220 and 1000 BC. In addition, short mineral-rich periods (26–60 year) exist between AD 1100 and 1800 and two longer periods up to 270 years rich in organic matter existed AD 980–1250 and AD 140–220.

We were able to distinguish two known climate periods, the cold event at around 900 BC and the Medieval Climate Anomaly at AD 980–1250. There are also minor evidences of the climate fluctuations during the Little Ice Age: two periods AD 1580–1630 and AD 1650–1710 indicate a slightly wetter and colder climate than today. In the Lake Korttajärvi sediment sequence, the effect of human impact has increased since the mid-18th century and has obscured the signal of natural climate variability.

Changes in the amount of accumulated mineral matter are caused most likely by changes in the North Atlantic Oscillation, which affects climate in the northern hemisphere.

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