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A multi-proxy analysis of climate impacts on the recent development of subarctic Lake Saanajärvi in Finnish Lapland

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Abstract

Responses to recent climatic changes in the sediment of subarctic Lake Saanajärvi in northwestern Finnish Lapland are studied by comparison of various biological and sedimentological proxies with the 200-year long climate record, specifically reconstructed for the site using a data-set of European-wide meteorological data. The multi-proxy evidence of simultaneously changing diatom, Cladocera, and chrysophyte assemblages along with the increased rates of organic matter accumulation and pigment concentrations suggest that the lake has undergone a distinct typological change starting from the turn of the 20th century. This change, indicating an increase in lake productivity, parallels a pronounced rise in the meteorologically reconstructed mean annual and summer temperatures in the region between ca. 1850 and 1930's. We postulate that, during the Little Ice Age, the lake was not, or was only weakly, thermally stratified during summer, whereas the subsequent increase in air and hence epilimnetic water temperatures resulted in the development of the present summer stratification. The increased thermal stability of the lake created more suitable conditions for the growth of phyto- and zooplankton and changed the overall primary production from benthos to plankton. Mineral magnetic and carbonaceous particle records suggest long-distance pollution, particularly since the 1920's, yet the observed changes in lake biota and productivity can hardly be explained by this very minor background pollution; the 20th century species configurations are typical of neutral waters and do not indicate any response to pollution.

Introduction

High-latitude regions react swiftly to environmental change, and changes in these regions are reflected via many feedback mechanisms in the global state of the environment. Most general circulation models (GCMs) suggest that within 70 years the Arctic will warm by at least 4 °C on an annual average and in places by more than 8 °C, i.e., 2–3 times more than the global average (Houghton et al., 1996). Long-term monitoring data are generally lacking, so it is impossible to directly determine background climatic and environmental variability or to track the spatial or temporal patterns of past

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environmental changes in the Arctic. To evaluate the present situation, high-resolution indirect proxy records must be used to infer past background environmental conditions.

Lakes and ponds are integral features of northern landscapes, and they are considered to be particularly sensitive reflectors of environmental change, including climatic fluctuations (Douglas et al., 1994; Rouse et al., 1997; Vincent & Pienitz, 1997; Blom et al., 1998, 2000; Korhola et al., 2002). Small water volumes, long ice-cover periods, and a short growing season make them particularly susceptible to changes in external loadings which can be induced by, for example, climate change. The expected effects of climate change on arctic lakes include changes in ice conditions, retention times, thermal conditions, light regimes, and water levels, as well as changes in the productivity and the structure of lacustrine ecosystems (Rouse et al., 1997; Blom et al., 1998). Lake biota may respond quickly to climate-driven changes in lake processes, either directly (e.g., temperature) or indirectly (pH, nutrients) (Smol et al., 1991; Psenner & Schmidt, 1992). Because changes in biota along with other changes in lake conditions can usually be detected in the sediments, arctic lake sediments potentially provide a unique temporal record of climatic change.

Here we examine the recent development of the subarctic Lake Saanajärvi in Finnish Lapland to document possible climate signals in its bottom sediments. The lake is the Finnish site in the European-wide research project ‘Mountain Lake Research’ (MOLAR), funded by the European Community (Battarbee et al., this issue (a)) The site has been monitored for physical, chemical, biological and sedimentological features since 1996. This study is an extension of an earlier study by Sorvari and Korhola (1998) in which we demonstrated that there is a distinct change in the sediment diatom community composition of the lake that occurred approximately 100–150 years ago and which has persisted to the present. We developed several hypotheses to explain the recent change, including (i) airborne pollution, (ii) climatic change, and (iii) catchment disturbances. Our evidence favoured the post-Little Ice Age (LIA) climatic warming as the main causative mechanism for the observed change, although we could not categorically exclude the other explanations.

In the present paper, several new independent proxy sources, such as chrysophycean cysts, chironomids, cladocerans, plant pigments, mineral magnetic analyses, and various sediment quality indices along with a more detailed diatom analysis are used to examine the environmental history of the lake and the extent of the ecosystem change since the pre-industrial period. The organism groups listed above were specifically chosen because they are known to be sensitive indicators of thermal and other environmental conditions in high altitude/high latitude lakes (Lotter et al., 1997; Korhola, 1999; Olander et al., 1999; Korhola et al., 2000), while the selected sediment parameters are thought to provide information about catchment disturbances (mineral magnetic records) as well as atmospheric pollutants deposited on to a lake and its catchment (e.g., spheroidal carbonaceous particles, SCPs). We also present a radiometric chronology for the recent sediments of the lake that was lacking in our previous preliminary investigation. The sediment proxies are compared with certain key climatic parameters, specifically inferred for the site for the last ca. 200 years (1781–1997) on the basis of the available data-set of European-wide meteorological data. By means of the multi-proxy evidence we demonstrate that the lake has undergone a distinct typological change during its recent ontogeny. We also attempt to seek causes for this recent environmental change.

Study site

Lake Saanajärvi (69° 05′N, 20 °52′E), located in northwestern part of Finnish Lapland close to the Norwegian and Swedish borders, about 50 km from the Arctic Ocean (Figure 1), is a small, clear, dimictic, nutrient-poor subarctic lake with a surface area of 0.7 km^2 and maximum depth of 24.0 m. Climatically the region forms a transition zone between the North Atlantic oceanic climate and the Eurasian continental climate; the mean annual temperature is –2.6 °C, mean annual precipitation is 422 mm, and the growing season is about 100 days (Järvinen, 1987). The bedrock surface consists of Paleozoic Caledonian schist and gneiss; there are sedimentary rocks and dolomitic limestones beneath this in places.

Lake Saanajärvi is located in the treeless tundra at an altitude of 679.4 m a.s.l., almost 100 m above the local birch limit. The pine forest limit lies about 70 km to the south. The lake is oval in form, maximum length is 1400 m and maximum width is 750 m. The lake margins are generally steep, and there is a relatively large, even-bottomed deeper central area in the lake; the shorelines are rocky. There are no macrophytes in the lake, except some aquatic mosses at the outlet. The catchment, about 4.6 km^2, is covered mostly by bare

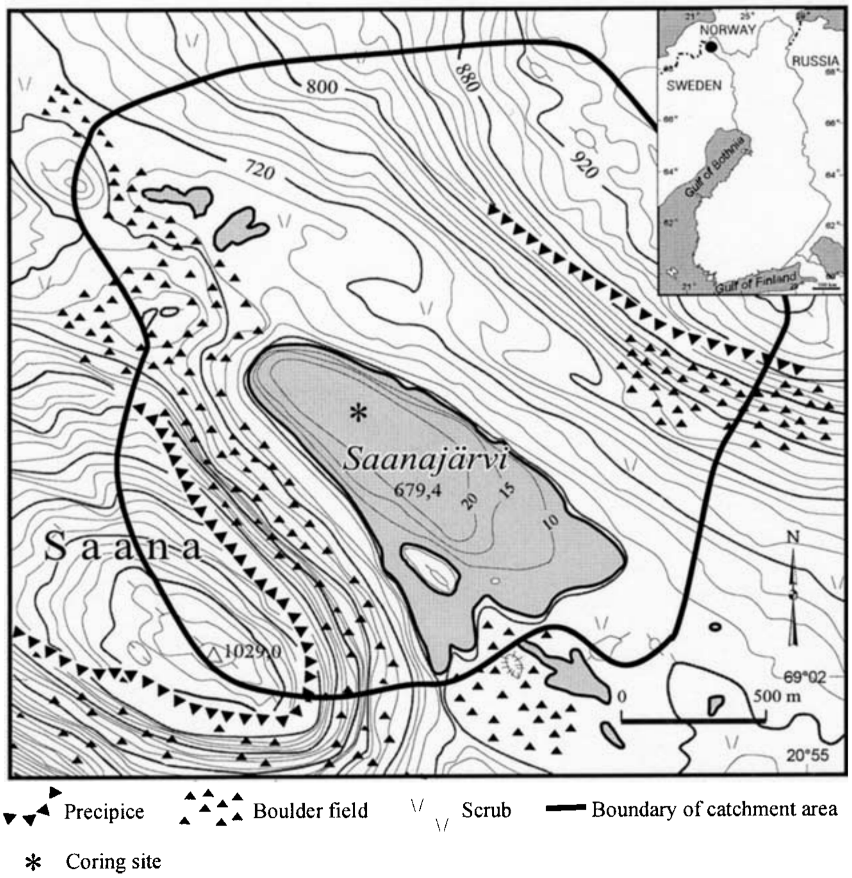

Figure 1. Map showing the location, catchment, bathymetry, sampling site and surroundings of Lake Saanajärvi in northwestern Finnish Lapland.

rocks and supports little soil. The catchment:surface area ratio is 6.6. There are no signs of direct human activity near the lake; the closest settlements (Kilpisjärvi) and roads are about 4 km away and lower in elevation. More details of the chemical and physical characteristics of the lake and its catchment are given in Sorvari and Korhola (1998) and Sorvari et al. (2000).

Methods

Coring and sampling

Four parallel sediment cores were taken in the central part of the lake from ice in May 1996 and an additional two cores in 1998 using a slightly modified Glew gravity corer, 5 cm in diameter. The first four cores were coded, lithologically described, and subsampled immediately in the field for various analyses at every 2-mm in the top 10 cm. The subsamples were stored in small plastic bags and kept cold at 4 °C. Two additional cores were extruded in the laboratory within 2 h of the coring at 5 mm (Cladocera) and 2 mm (C, N, S, pigments) intervals for the top 15 and 10 cm, respectively. While extruding, the sediment for Cladocera analysis was subsampled into two fractions; 2 cm^3 of wet sediment was placed in plastic tubes for biological analysis, whereas the rest of the sediment was placed in Eppendorf tubes and dried immediately for dry weight (DW) and loss-on-ignition (LOI) analyses. Samples for pigment analyses were frozen immediately. The core codes, various analyses, as well as the laboratories responsible for the analyses are indicated in Table 1.

Dating

Samples from the Lake Saanajärvi master core (SAAN-4) were analysed for ^{210}Pb, ^{226}Ra, and ^{137}Cs by direct gamma assay in the Liverpool University Environmental Radiometric Research Centre, using Ortec GWL series well-type coaxial low background intrinsic germanium detectors. The technical procedures are described in Appleby et al. (1986, 1992). The separate cores (Table 1) were correlated with the master core by the sequence slotting technique described in Thompson and Clark (1993). The variations in DW and LOI profiles, measured for each core at 2 mm resolution, were used in the correlations.

Sediment and chemical analyses

Water content (WC), DW and LOI were analysed according to standard methods. Due to the small amount of material available for the analysis, quartz crucibles were used instead of porcelain crucibles in order to improve accuracy. Total carbon (C), nitrogen (N) and sulphur (S) were determined by a NCS elemental analyzer (NA 1500, FISONS).

Spheroidal carbonaceous particles

SCP analysis followed the method described in Rose (1994). The number of SCPs on the coverslip were counted using a light microscope at 400× magnification and the sediment concentration calculated in units of 'number of particles per gram dry mass of sediment' (g DM^{-1}). The detection limit for the technique is 100 g DM^{-1} and concentrations have an accuracy of ± 45 g DM^{-1}.

Magnetic measurements

Room temperature magnetic measurements were made on 95 weighed and dried 0.2 cm contiguous samples in the depth range 1.0–20 cm in plastic film using a vibrating sample magnetometer, pulse magnetisers and spinner magnetometer. The upper 5 samples were of insufficient mass to be measured. This procedure provided continuous measurements of magnetisation in fields 0-1 T and remanence measurements following fields of 1T, –20 mT and –300 mT. Key magnetic parameters were calculated using the techniques described in Thompson and Oldfield (1986), Dearing et al. (1998), Walden et al. (1999).

Diatoms

0.2 g of wet sediment was prepared for diatom analysis according to the methodology described in Weckström et al. (1997a). Polystyrene microspheres were added to the samples for calculation of diatom concentrations. Simultaneously with the diatom counts, the total number of chrysophyte cysts was enumerated. A minimum of 500 diatom frustules were counted for each sample. Standard floras (e.g., Mölder & Tynni, 1967–73; Tynni, 1975–80; Camburn & Kingston, 1986; Krammer & Lange-Bertalot, 1986–91; Lange-Bertalot & Metzeltin, 1996) were used in the diatom identification. For the description of *Aulacoseira italica* subsp. *subarctica* type II, see Sorvari and Korhola (1998). The identification of arctic *Achnanthes* sp. I is based on unpublished notes of the Arctic-Antarctic Diatom Workshop held in Quebec, Canada, in 1997.

Cladocera and chironomids

Samples for Cladocera analysis were first heated for half an hour at about 80 °C in 150 ml 10% KOH using a magnetic stirrer. The liquid mixture was then poured onto a 50 µm sieve and rinsed under running tap water. The remaining sediment on the sieve was carefully washed into a 15 ml tube, and 2–3 drops of safranin-glycerin solution were added to colour the remains. The final volume of the sediment-water mixture in each tube was 10 ml. Two slides were prepared from each sample by first homogenizing the tube contents by

Table 1. Lake Saanajärvi sediment core data: the core codes, coring dates, various analyses, and the laboratories responsible for the analyses

Core code	Coring date	Analyses made	Responsible laboratory
SAAN-1	May 1998	LOI, DW, C, N, S, pigments	DES (LOI, DW), CNR
SAAN-2	May 1996	LOI, DW, chironomids	DES
SAAN-3	May 1996	LOI, DW, diatoms, chrysophyte cysts	DES (LOI, DW, diatoms), ECRC (chrysophytes)
SAAN-4 (master core)	May 1996	LOI, DW, dating, SCP, magnetics	ERRC (dating), EML (magnetics), ECRC (SCP)
SAAN-5	May 1998	LOI, DW, cladocera	DES
SAAN-6	May 1996	A back-up core	

DES = Department of Ecology and Systematics, University of Helsinki, FI; CNR = Ist.Ital.Idrobiol., Pallanza, Italy; ECRC = Environmental Change Research Centre, University College London, UK; ERRC = Environmental Radiometric Research Centre, University of Liverpool, UK; EML = Environmental Magnetism Laboratory, University of Liverpool, UK.

shaking and then pipetting 200 µl of the sample onto an object glass. Both slides were counted at magnifications of 120–240× and the resulting number standardised to 1 cm^3. Due to low abundance of most of the species, only *Daphnia longispina* was used for further analysis. All *Daphnia* remains were counted, but only the number of the most frequent remain, a shell of a parthenogenetic egg, was used as an index for the species abundance.

The sediment was found to be extremely poor in chironomid remains; head capsules, usually in poor condition, were found only occasionally. Amalgamation of contiguous samples did not improve the outcome. Because of the poor representation, the results of the chironomid analysis are discarded in the present study.

Chrysophyte stomatocysts

Sample and slide preparation for chrysophyte stomatocyst analysis followed similar procedures to those used for the preparation of diatoms, except that microspheres were not added. Cysts were analysed under the light microscope at a magnification of ×1200 using a combination of bright-field, phase contrast and differential interference contrast illumination. The counting sum was 60–100 cysts per sample. An internal cyst taxonomy was used, although this was based on the concepts presented in Duff et al. (1994). With the exception of the ‘stomatocyst 17’ it was possible to match cysts with published taxa. However, for the purposes of this analysis, an internal taxonomy of cyst types has been retained.

Plant pigments

Chlorophylls and their derivatives (CD) and total carotenoids (TC) preserved in the sediment were measured spectrophotometrically on an acetone extract of ca. 1 g wet sediment. CD was expressed as spectrophotometric units per g organic matter (U g LOI^{-1}, Guilizzoni et al., 1983) while TC was expressed as mg g LOI^{-1} (Züllig, 1982). On the same acetone extract, a reverse-phase HPLC chromatographic analysis was performed to identify the single carotenoid and chlorophyll. The method used for the determination of specific algal pigments is described in detail in Lami et al. (2000). All the chlorophyll and carotenoid compound isolated by HPLC were reported as nMoles per g organic matter.

Reconstructions and climate correlations

Diatoms were used to reconstruct pH by weighted averaging partial least squares (WA-PLS) regression based on the AL:PE project calibration data-set of 118 lakes from European mountain regions (Cameron et al., 1999). The data-set has been screened to include only appropriate arctic and alpine lakes and has a harmonised diatom taxonomy. The pH range in the data-set is 4.5–8.0. The predictive power of the training set, as assessed by statistical cross-validation, is 0.33 pH units for the 3-component WA-PLS model.

Linear regressions between the available sediment core variables (response variables) and reconstructed climate records (predictor variables) were performed using the statistical procedures and tools described by Battarbee et al. (this issue (a)). The predictor variables consist of six climatic ’summary’ variables, which have been reconstructed for the site on a yearly basis from 1781 AD using an extensive data-set of local (automatic weather station), regional (north-Fennoscandian climate stations) and European-wide meteorological data (Augusti-Panareda & Thompson, this issue). The six summary variables are: (1) the mean June, July and August temperature (JJA); (2) the mean July, August and September temperature (JAS); (3) the mean September, October and November temperature (Aut); (4) the mean December, January and February temperature (Wint); (5) the absolute difference between JJA and Wint (a continentality index, Cont); and (6) the mean temperature of all twelve months (Ann). Three different LOESS smoothers, using spans of 0.5, 0.1 and 0.05, were used to calculate the averages of each climate index, yielding a total of 18 predictor variables. The initial taxon data is summarized in the regressions in the form of principal components (see Battarbee et al., this issue (a)). The midpoint of each analysed section in the core is taken to represent the sample depth. Because various response variables have been analysed from different sediment cores, extreme caution should be exercised when interpreting the regressions, as even slight irregularities in sediment accumulation rate or mistakes in core correlations may cause substantial bias to the results (Battarbee et al., this issue (b)).

Results

Lithostratigraphy

The sediment is composed of a relatively minerogenic gyttja with LOI values varying in the range 14–26%

(Figure 2). Such LOI values are typical for arctic and subarctic sites with low primary production and low input of allochthonous organic matter from their rocky catchments (Korhola et al., 1999). There is a gradually increasing trend in LOI towards the sediment surface observable in all cores, the most distinct increase occurring in the core SAAN-4 at a level of 4–5 cm. In addition to this general trend there is also a much finer-scale fluctuation of 1–2% evident in all cores; these spikes are used to correlate the cores (Figure 2).

C, N and S concentrations proved to be significantly related to LOI ($p \leq 0.01$) and show a very similar trend (Figure 3). All the profiles show lower values from the bottom of the core to a level of ca. 7 cm. Above this, they show a steady increase to the top of the core. This increase is less evident in the sulphur profile, however. The C:N ratio (Figure 3) points to a prevalent autochthonous origin of the organic matter since the values are just above or very near to 10. Slightly higher values are observed in the lower core section (7–10 cm).

The basic colour of the upper sediment layer is light grey although there are several reddish-yellowish bands intercalating the sediment particularly in the 5–10 cm interval. The alternating layers of different colours are easily seen by eye. The layers with reddish-yellow colour result most probably from oxidation by the oxygen-saturated bottom waters.

Chronology and sediment accumulation rates

In the dated master core equilibrium between total ^{210}Pb and the supporting ^{226}Ra, corresponding to ca. 150 years accumulation, was reached at a depth of about 6 cm. ^{226}Ra activity remained relatively constant throughout the core, with a mean value of 39 Bq kg^{-1}. Unsupported ^{210}Pb concentrations were a little irregular in the top 1.5 cm, but beneath this declined more or less exponentially with depth suggesting relatively uniform sediment accumulation rates in the older sediments. The ^{137}Cs activity versus depth profile had two significant peaks, at 0.7 and 1.5 cm (Figure 4). It is presumed that the more recent feature records fallout from the Chernobyl reactor accident in 1986, and that the earlier feature records the 1963 fallout maximum from the atmospheric testing of nuclear weapons. This is supported by ^{210}Pb dates (calculated using the CRS model) which place 1986 at a depth of ca. 0.6 cm and 1963 at a depth of ca. 1.7 cm. The mean accumulation rate during the past 30 years is calculated to be 0.025 ± 0.005 g cm^{-2} yr^{-1} (0.053 ± 0.010 cm yr^{-1}). The mean accumulation for the 150 years preceding ca. 1960 is calculated to be 0.012 ± 0.001 g cm^{-2} yr^{-1} (0.024 ± 0.002 cm yr^{-1}). Due to the large standard errors arising from the small sample sizes too much significance should not be attached to the irregular fluctuations in

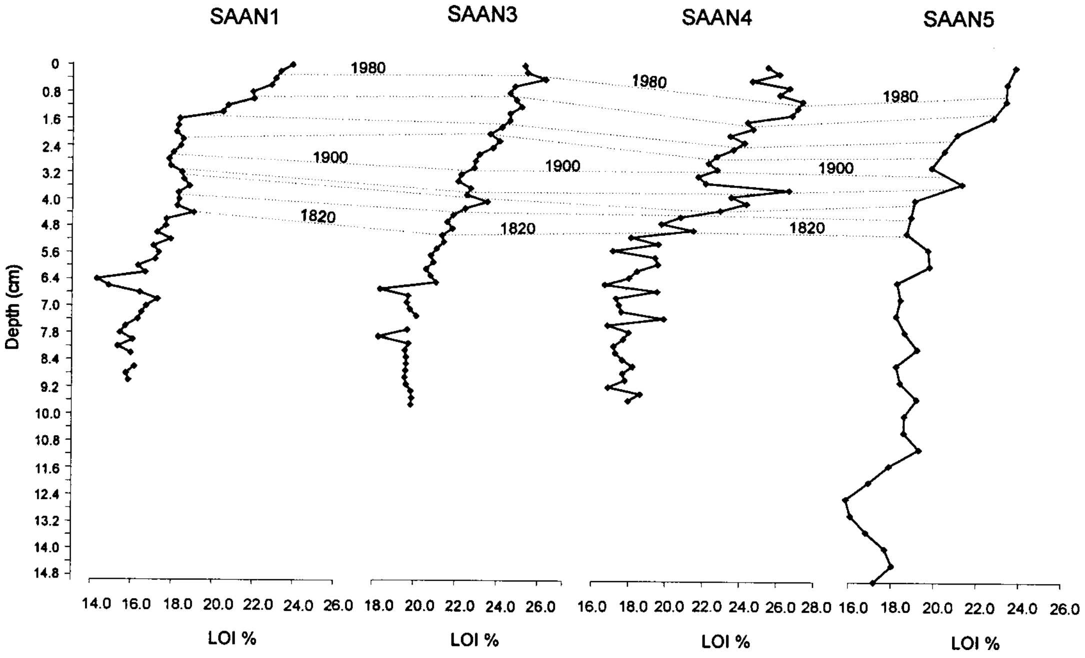

Figure 2. Variation in loss-on-ignition (LOI) in the parallel sediment cores analysed for various sediment proxies.

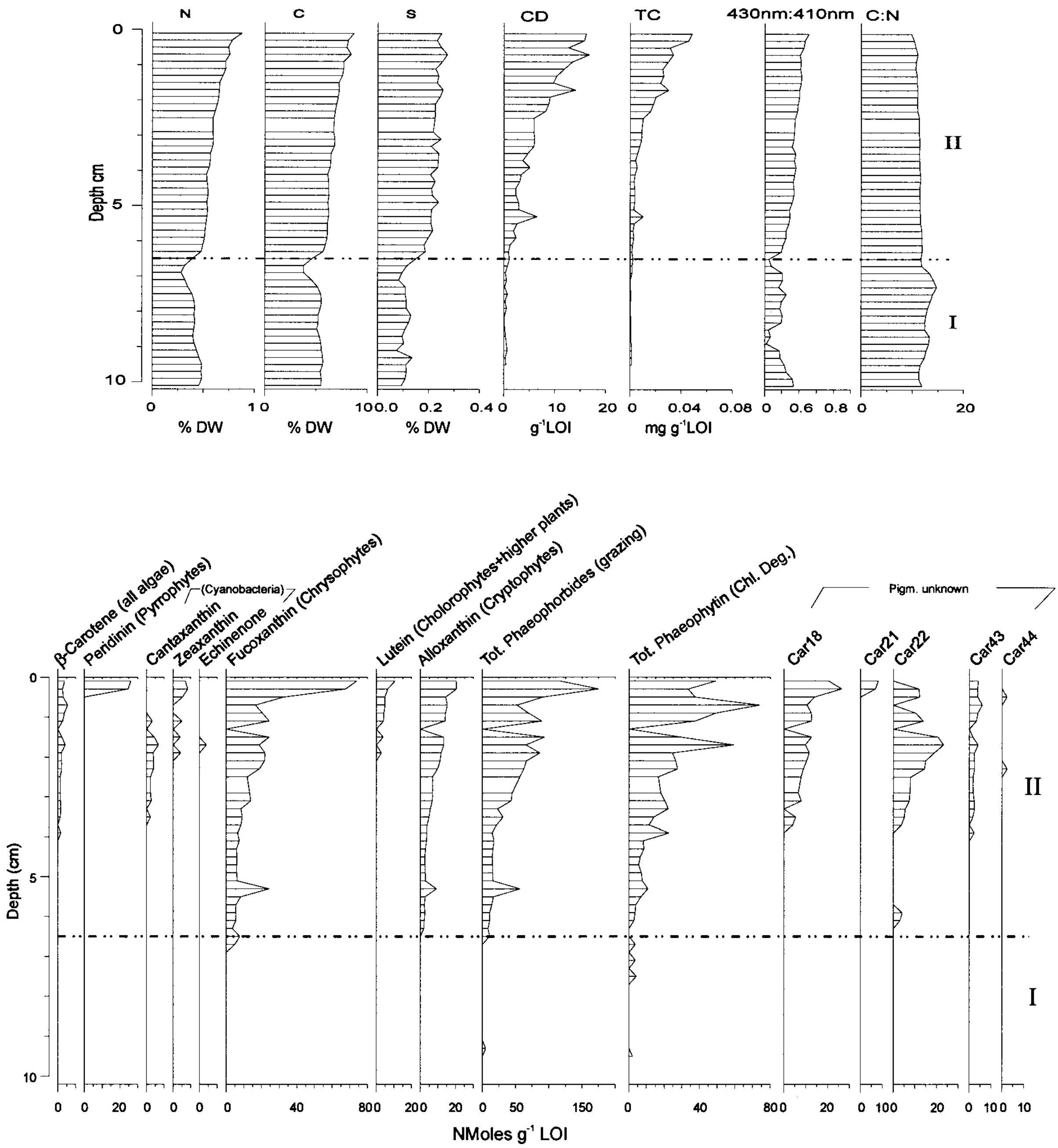

Figure 3. Concentrations of N, C, S and fossil pigments in the sediment core (SAAN1) of Lake Saanajärvi. Zoning is based on the most abrupt change in the pigment record.

sedimentation rates shown in Figure 4, though there may have been a small secular increase during this period. Sediment accumulation rates in the neighbouring cores are similar to those in the master core, suggesting relatively stable accumulation conditions throughout the deeper basin.

In general, sediment accumulation rates in lakes vary according to the input of both organic and inorganic material from the lake catchment and biogenic material from the lake itself. In oligotrophic systems, such as the lake studied here, material derived from the catchment usually dominates (see the pigment section).

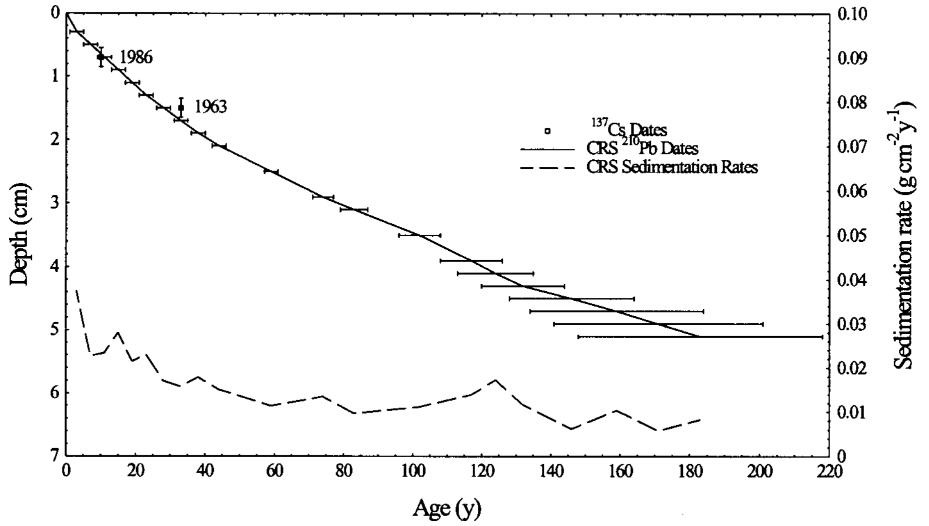

Figure 4. Constant rate of supply (CRS) ^{210}Pb dates vs. sediment age and CRS sediment accumulation rates. Also shown are the 1963 and 1986 levels determined from the artificial radionuclide records.

The extremely slow sediment accumulation rate observed at Saanajärvi is typical for arctic sites with rocky catchments and low primary production (Douglas et al., 1994; Korhola et al., 1999).

Spheroidal carbonaceous particles

The results of the SCP analyses for the sediment core SAAN-4 are shown in Figure 5. In general terms the SCP profile shows similar characteristics to those found throughout Europe. SCP concentrations increase steadily from ca. 4 cm and more rapidly above 3 cm. A number of concentration peaks are observed and the irregular nature of the profile near the surface may be due to the low concentrations present in the core. Converting the SCP concentrations to SCP accumulation rates removes some of these irregularities and emphasises the 'European pattern'. Again, the SCP accumulation rate profile begins at ca. 4 cm (ca. 1880) and increases steadily to 2–2.5 cm (1937–1953 ± 2) when a more rapid increase is observed to a peak at 0.7 cm (1985 ± 2). A general decline is then observed between this depth and the sediment surface.

In European terms, the rapid increase is usually found in the 1950's as a result of the post-War boom in the electricity generation industry and the introduction of cheap fuel-oil leading to the first large scale oil-fired power stations. This feature in the Saanajärvi core could therefore be earlier than the general pattern. However, sediment metal records from lakes in the Kola Peninsula show increases above background from the 1920's and 1930's (Norton et al., 1992) whilst the smelter at Nikel began operations in 1946. 'Local' influences may therefore partly explain this result.

In spatial terms, the surface sediment SCP concentration of ca. 800 g DM^{-1} agrees well with the values observed in other studies of northern Scandinavian sites. For example, Wik and Renberg (1991) typically found concentrations between 100–2000 g DM^{-1} in northern Sweden; Rose et al. (in press) found concentrations of between 200–1000 g DM^{-1} in surface sediments on Svalbard and similar concentrations in Arctic sites in both the Siberian and Canadian Arctic and on Iceland (unpublished data). Korhola et al. (1999) found concentrations up to 10,000 g DM^{-1} in north-east Finland, close to the emission sources from the Kola smelter industry. Arctic lake sites on the Kola Peninsula have been found to have higher SCP surface concentrations than other sites in northern Europe (Rose, 1995).

The surface SCP accumulation rate also fits well with the proposed European pattern (Rose et al., 1999). Converting the full sediment profile to an inventory provides a single cumulative figure for the whole post-industrial period and thus allows a better inter-site comparison as within-lake variability is, to a certain extent, accounted for. The inventory for SAAN4 is 167 × 10^5 SCP m^{-2} which is higher than other northern European sites (Arresjøen, NW Svalbard = 3.16 × 10^5; Øvre Neådalsvatn, mid-Norway = 24.8 × 10^5), but this again

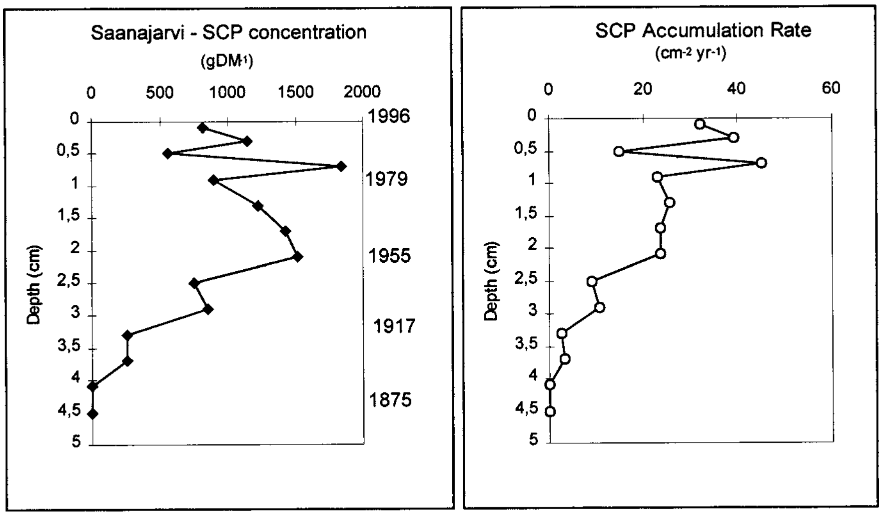

Figure 5. Spheroidal carbonaceous particle (SCP) concentrations (g DM^{-1}) and accumulation rates (cm^{-2} yr^{-1}) for SAAN4.

may be due to the influence of sources on the Kola Peninsula. However, variation between sites may still exist due to, for example, the in-wash of atmospheric pollutants from catchment sources and these can be compensated for by normalising the SCP inventories to ^{210}Pb inventories. The resulting ratio provides an index of pollution for the whole deposition period and allows a good inter-site comparison of SCP atmospheric deposition (Rose et al., 1999). For Saanajärvi this ratio fits well with the latitudinal pattern suggested by Rose et al. (1999).

Magnetic records

Curves for concentrations of ferrimagnetic (χ_{low}), and low coercivity ferrimagnetic (soft IRM) minerals (Figures 6a & 6b) show little trend in values upcore until ~ 5–6 cm (early 19th century). Low coercivity ferrimagnetic concentrations rise steadily during the 19th century, reach peak values during the 1950's followed by a minimum in the late 1960's (sediments deposited after ~ 1977 were not measured). The curve for concentrations of imperfect antiferromagnetic minerals (HIRM) (not shown) shows a similar pattern to Soft IRM in the upper 10 cm but shows peak values in deeper sediments ~ 12.5–13.5 cm (not shown). Concentrations of paramagnetic Fe-bearing minerals (χ_{high}) (Figure 6c) show constant values throughout the sequence except for a significant drop in values at 4.3 cm.

Ratio parameters give qualitative information about the mineral assemblages and two distinct trends are observed. Above a depth of 15 cm, values of soft IRM % increase upcore (Figure 6d) while values of χ_{high} % (Figure 6e) and HIRM % (not shown) fluctuate around a declining trend upcore. These opposing trends may be explained by proportions of low coercivity 'multidomain' magnetite increasing upcore relative to the high coercivity imperfect antiferromagnetic and paramagnetic minerals. Relatively low and constant values of M_{rs}/χ_{low} (Figure 6f) suggest that the authigenic iron sulphide, greigite, is not an important ferrimagnetic mineral, except possibly at 4.3 cm. Values of H_c (~ 5–10 mT) fall within the range (not shown) indicative of relatively low coercivity minerals and domains, such as multidomain magnetite. There is no strong evidence for a dominance by mineral dissolution, magnetosomes or greigite in any section. Small-scale fluctuations in magnetic parameters may show discrete detrital influx events, but equally significant changes in particle-size caused by turbidites, diatom silica and different hydrological processes may be important.

Pigment records

According to the pigment profiles observed in the SAAN1 core, two zones could be recognised: zone I (core base – 6.5 cm) with extremely low pigment values; and zone II (6.5 cm – surface) showing steady increases in particular of CD and TC (Figure 3). A slight increase in 430 nm:410 nm ratio is also shown, starting from 6 cm upwards. This ratio shows very low values at 6.5–7 and 8.5–9 cm indicating a period of poorer pigment preservation probably due to more oxidising conditions (for the changes in sediment col-

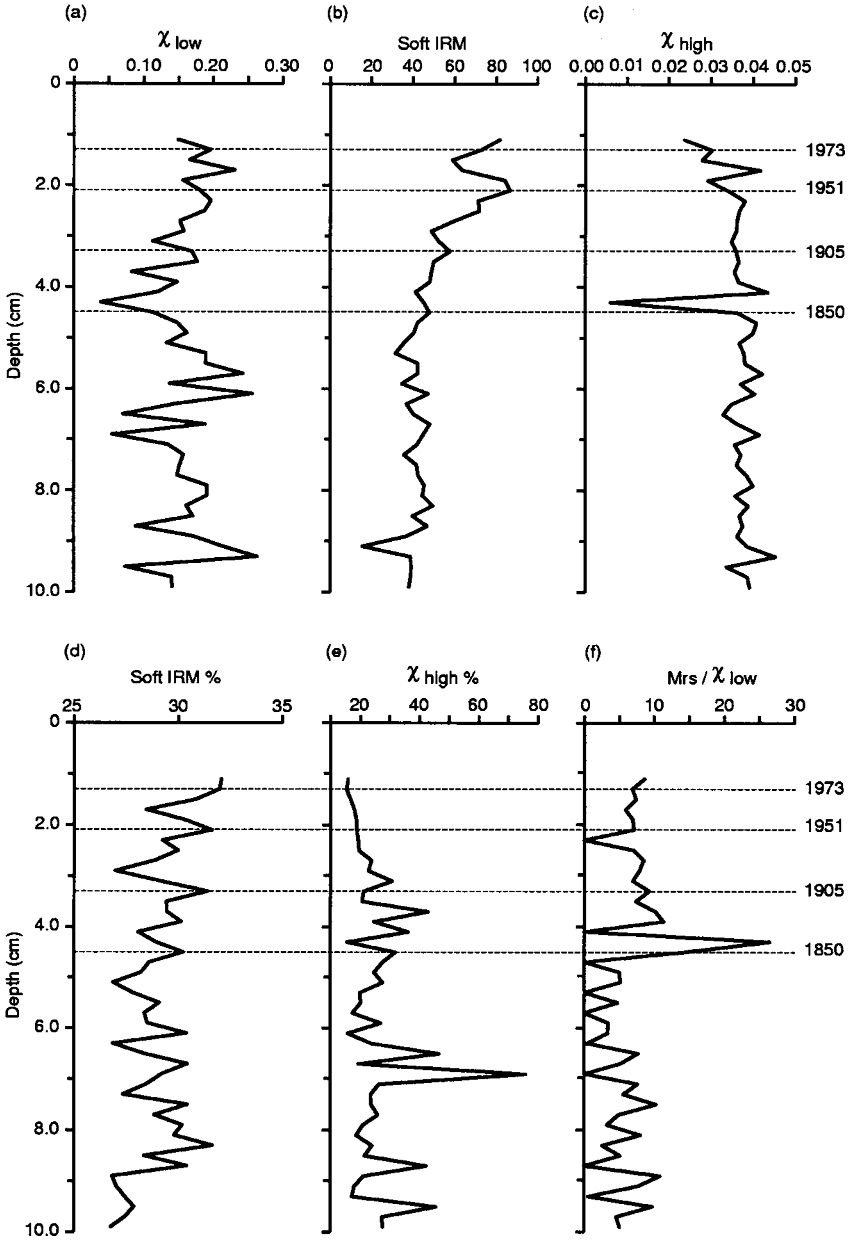

Figure 6. Selected magnetic measurements: (a) mass specific susceptibility (χ_{low} 10^{-6} m^3 kg^{-1}); (b) mass specific soft IRM (soft IRM mA m^2 kg^{-1}); (c) mass specific paramagnetic susceptibility (χ_{high} 10^{-6} m^3 kg^{-1}); (d) per cent soft IRM (soft IRM %); (e) per cent paramagnetic susceptibility (χ_{high} %); (f) ratio saturation remanence: susceptibility (M_{rs}/χ_{low} kA m^{-1}).

our and their interpretation, see above). Compared to other remote sites included in the MOLAR programme, the total pigment concentrations are among the lowest for all lakes.

In general, the specific pigments are reduced in number and their concentrations are very low. They appear from ca. 6 cm onward. Colonial cyanobacteria (oscillaxanthin and myxoxanthophyll) are absent, while siliceous algae (peridinin, fucoxanthin and alloxanthin) are most abundant (Figure 3). The pigment records indicate an environment of low productivity. At the very top of the core (0–6 mm), there is an increase in fucoxanthin and peridinin that parallels the change in diatom composition (as indicated by the diatom PCA axis 1; Figure 9) and the increased diatom total accumulation rates. This increase seems therefore to be related more to a real increase in the lake productivity rather than a pigment diagenesis effect.

Diatom analysis and pH reconstruction

A total of 203 diatom taxa representing 30 genera were identified in samples from the 10-cm sediment core, consisting predominantly of benthic species. *Cyclotella comensis*, *C. glomerata*, *C. rossii*, *C. schumannii*, *Thalassiosira pseudonana* and *Aulacoseira italica* subsp. *subarctica* type II, as well as various *Achnanthes* and *Fragilaria* species were the most abundant taxa found. The lowermost part of the core, at 10^{-4} cm, was characterised by high relative abundance of benthic/periphytic species as well as *rossii*-type *Cyclotella*s. This was followed by an increase in the abundance of planktonic/tychoplanktonic taxa in the younger horizon (approximately 1900 onwards) (Figure 7). This floristic change is clearly shown in scores of the diatom PCA axis 1. (Figure 9). The distribution of planktonic diatom taxa along axis 1 in the ordination shows that the axis can be considered as a 'habitat' axis, indicating an increase in the planktonic component and possibly also lake primary production from the older sediment layers to the younger strata. The highly meaningful PCA axis 1 explained 37.6% of the total variation in diatom data.

There is only a minor trend in the diatom-inferred pH values with all pH variation lying within the standard error of the model estimate. The values are markedly constant (≈ 6.8) in the lower part of the studied sequence, followed by a slight increase in reconstructed values in the upper part (1900–present) of the core (Figure 7). However, no corresponding increase in pH was observed when the pH was reconstructed by means of the local northern Fennoscandian diatom–pH training data-set (Weckström et al., 1997b) instead of the AL:PE calibration data-set (results not shown). In general, there is a rather poor fit above 3 cm between core samples and samples in the AL:PE surface sediment data-set; a total of 40 taxa present in the core material are absent in the AL:PE calibration data-set.

Chrysophyte cysts

A total of 63 taxa were identified. Given the low counting sum, as one might expect, the cyst percentage data are somewhat noisy and significant changes in their percentages are not apparent (Figure 8). The assemblages are dominated by unornamented cysts with

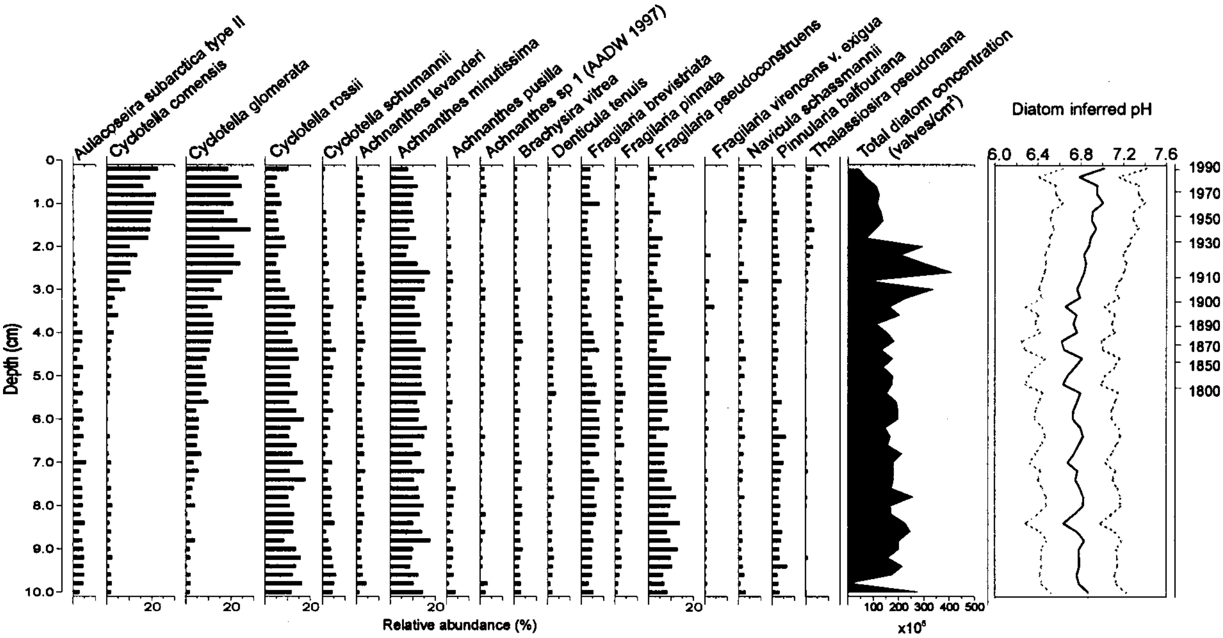

Figure 7. Relative frequency diagram of the most dominant diatom taxa, total diatom concentrations (number of valves per cm^2) and diatom-inferred pH with sample-specific errors of prediction for Lake Saanajärvi (SAAN4). pH was reconstructed using the AL:PE calibration data-set and a three-component WA-PLS model (Cameron et al., 1999).

pores, in the size ranges of less than 5 µm and from 5–10 µm in diameter (taxa A4 and A5 respectively). Overall there appears to be a decline in the percentage of the former taxon, from abundances of over 60% near to the base of this section of the core to percentages of 30% or less at the top of the profile. Unornamented cysts with a collar, in all size ranges (A1, A2, A3) become more common towards the top of the profile. Some taxa e.g., E4 (two maxima in the lower part of the core and reappears at the surface) seem to show restricted distributions whilst others e.g., A6, are fairly evenly distributed throughout the profile. However, given the absence of ecological data for these cysts it is not possible to speculate on the reasons for these small changes. Further, given the low counting sum it is unreliable to argue from the abundances of the rarer taxa.

Cladocera

The sediment of Lake Saanajärvi was found to be poor in cladoceran remains; only 10 taxa were identified and mostly in very low numbers. *Daphnia longispina* dominated throughout the core with the proportions always exceeding 50% of the total number of Cladocera remains. Until 1900 the cladoceran community seemed to have been extremely scarce, after which there is a distinct increase especially in the *D. longispina* population (Figure 9).

Regressions with climate variables

Table 2 lists the r^2 values (or the fraction of the variance explained) for linear regressions between the reconstructed climate variables and the biological and sedimentological indicators. Statistically significant ($p \leq 0.01$ and $p \leq 0.05$) relationships are marked in the table. Also relationships between sample depth in each core (Depth 1, 3, and 5) and climate variables are shown. Due to strong autocorrelations between samples, the p-values must be interpreted with caution.

From the six climatic predictor variables used in the linear regression analyses, annual mean temperature using the largest smoother span (Ann1, span 0.5), showed strongest relationships to the sediment response variables (10 regressions with $p \leq 0.01$; Table 2). Most of these relationships are stronger than the corresponding relationships of climate variables to sample depth. In addition to annual mean temperature, winter temperature and continentality index showed significant correlations with many of the sediment proxies. Among the biostratigraphical data, both diatom and cladoceran assemblages yielded larger eigenvalues than expected by randomness for the PCA axis 1, while the first PCA axis for chrysophyte data was weakly non-significant as assessed by the broken stick model. However, for cladocerans it is striking that benthic Cladocera PCA axis 4 shows a better response to the climatic variables than both axes 1 and 2, even if only

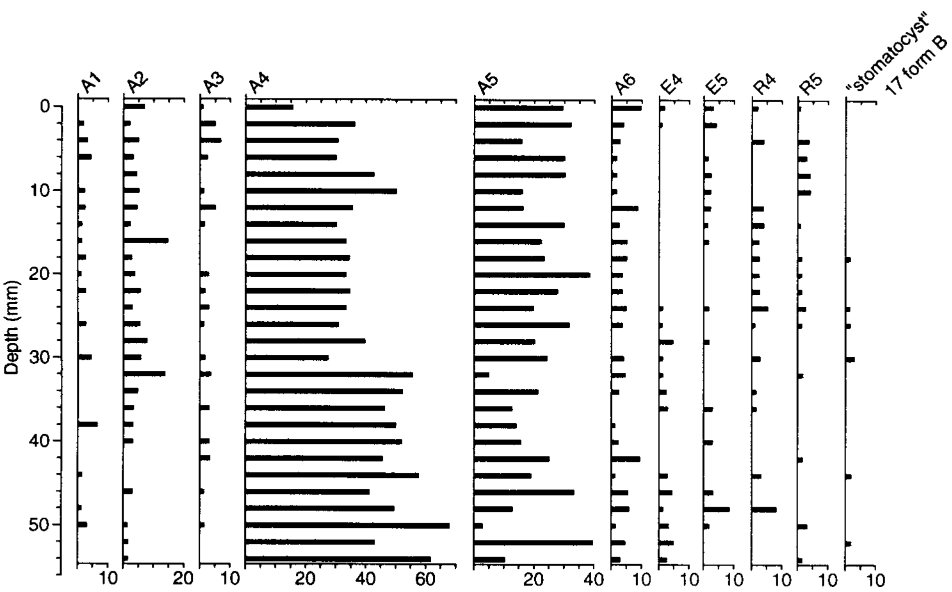

Figure 8. Percentage diagram of the most common chrysophyte taxa for Lake Saanajärvi.

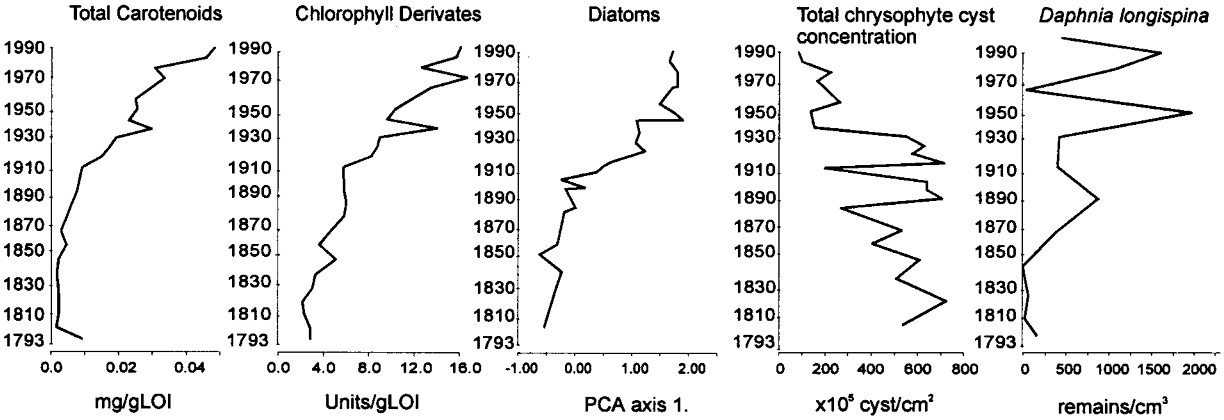

Figure 9. Summary figure of selected sediment variables documenting the change in the recent history of Lake Saanajärvi. Also reconstructed annual mean temperature (a 5-year running mean) for Lake Saanajärvi is shown for comparison. This reconstruction is based on the work by Agustí-Panareda and Thompson (this issue). For more detailed discussion about the various records, see text.

7.2% of the species composition is explained by this axis, which is less than expected for this fourth axis by the broken stick model. Among planktonic Cladocera, PCA axis 1 seems to be related with annual mean temperature, whereas PCA axis 2 shows some correlation to autumn mean temperatures. Nevertheless, all biological records summarized in the form of PCA components were statistically significantly correlated with the reconstructed annual mean temperatures, as were also the variables LOI, CD, TC, CD:TC, and DpH. From the single response variables, planktonic diatoms (0.67), total diatoms (0.63) and chrysophyte cysts (0.59) showed highest correlations to annual mean temperature, whereas planktonic Cladocera were found to be markedly related with autumn temperatures. These results suggest that all the biological variables selected for the present study show significant relationships to climate and can thus be considered as sensitive response variables to climatic variability. However, when interpreting the results, one should remember that in the case of cladocerans and chrysophytes, in particular, the PCA is based on a rather low counting sums.

In Figure 9, some of the most responsive sediment proxies are contrasted against the mean annual temperature reconstructed for Lake Saanajärvi (Agustí-Panareda & Thompson, this issue). There is a marked correspondance in the patterns of all sediment proxies and the inferred temperature trends, the reasons for which are discussed below.

Discussion

The remote subarctic Lake Saanajärvi has clearly gone through a marked environmental change during its recent history. The most striking transition in the sediment sequence is to be seen at approximately 3 cm (1900 AD), where new species assemblages started to form (Figure 9). The observed re-organization is predominantly from benthos to the present-day planktonic dominants in all biological proxies. This typological change is most clearly documented by diatoms, which show a marked increase in the relative proportions of centric and planktonic *Cyclotella comensis* and *C. glomerata* species that replace the earlier diatom assemblages dominated by pennate and benthic/periphytic *Achnanthes* and *Fragilaria* taxa. There is also a corresponding increase in pigment (fucoxanthin and peridinin) and total planktonic chrysophyte cysts concentrations, accompanied by a sharp increase in organic matter accumulation. The sharp increase in frequencies of filter-feeding zooplankton, especially *Daphnia* (Figure 9), is most probably in response to the increasing concentration of suitable food organisms. All the recorded changes are thought to reflect increased productivity of the lake from ca. 1900 onwards.

In an earlier paper, Sorvari and Korhola (1998), on the basis of diatom data, presented three hypotheses, including catchment disturbance, atmospheric pollution and climate change, to explain the observed 20th century change. With the extensive multi-proxy data now available from the sediment record of Lake Saanajärvi it is possible to re-evaluate these hypotheses. As concluded in the earlier paper, direct catchment impact by humans can almost certainly be ruled out as a cause for the observed change in sediment as the area is remote, rocky, sparsely vegetated and thus unsuitable for human land-use. However, the increased reindeer herding in the area during the last few decades might

Table 2. Fraction of the variance explained (R-squared) for linear regressions between reconstructed climatic variables (with three different LOESS smoothers: 1: span = 0.5; 2: span = 0.1; 3: span = 0.05) and physical and biological sediment proxies (* and **indicate significant correlations at $p \le 0.05$ and $p \le 0.01$, respectively). Only the most responsive sediment parameters are shown

	Depth 1	LOI1	CD	TC	CD.TC	Pigm. PCA1	Diatoms PCA1	Plank. diatoms PCA1	Benthic diatoms PCA1	DpH	Depth 3	LOI3 PCA1	Chrys.
JJA1	0.22	0.05	0.05	0.04	0.08	0.10	0.00	0.00	0.00	0.00	0.05	0.01	0.00
JJA2	0.10	0.05	0.02	0.02	0.07	0.05	0.00	0.00	0.00	0.02	0.01	0.00	0.04
JJA3	0.12	0.12	0.04	0.05	0.10	0.04	0.00	0.00	0.00	0.02	0.01	0.00	0.02
JAS1	0.42**	0.14	0.21*	0.17*	0.20*	0.28**	0.04	0.04	0.04	0.01	0.13	0.05	0.03
JAS2	0.29**	0.17*	0.14	0.12	0.14	0.19*	0.03	0.02	0.04	0.00	0.09	0.03	0.00
JAS3	0.30**	0.30**	0.18*	0.17*	0.18*	0.19*	0.01	0.01	0.03	0.00	0.04	0.02	0.00
Wint1	0.40**	0.02	0.25**	0.21*	0.39**	0.31**	0.32**	0.35**	0.21*	0.20*	0.29**	0.26**	0.43**
Wint2	0.10	0.00	0.05	0.05	0.15*	0.06	0.03	0.04	0.02	0.06	0.02	0.02	0.12
Wint3	0.09	0.00	0.03	0.02	0.08	0.02	0.04	0.04	0.02	0.07	0.04	0.03	0.12
Cont1	0.47**	0.04	0.23**	0.19*	0.36**	0.32**	0.22**	0.25**	0.15*	0.10	0.27**	0.19*	0.28**
Cont2	0.20*	0.01	0.08	0.08	0.24*	0.12	0.03	0.03	0.01	0.03	0.04	0.02	0.06
Cont3	0.17*	0.02	0.05	0.05	0.15*	0.05	0.04	0.04	0.03	0.03	0.06	0.03	0.05
Ann1	0.50**	0.15	0.49**	0.45**	0.56**	0.37**	0.63**	0.67**	0.50**	0.51**	0.49**	0.53**	0.59**
Ann2	0.13	0.01	0.14	0.15*	0.12	0.10	0.17*	0.17*	0.14	0.23**	0.12	0.17*	0.30**
Ann3	0.10	0.00	0.06	0.07	0.08	0.05	0.14*	0.15*	0.12	0.19*	0.14	0.16*	0.26**
Aut1	0.32*	0.11	0.29**	0.18*	0.22*	0.10	0.39**	0.40**	0.32**	0.33**	0.31**	0.40**	0.28**
Aut2	0.13	0.02	0.16*	0.13	0.04	0.12	0.19*	0.19*	0.17*	0.24**	0.18*	0.20*	0.17*
Aut3	0.08	0.00	0.09	0.07	0.05	0.06	0.08	0.08	0.08	0.14*	0.10	0.11	0.11

JA = mean temperature June, July, August; JAS = mean temperature July, August, September; Wint = mean temperature December, January, February; Cont = absolute difference between JJA and Wint; Ann = annual mean temperature; Aut = mean temperature September, October, November.

Table 2. Continued

Total Chrysoph. Consentr.	Depth 5	Benthic Cladocera PCA1	Benthic Cladocera PCA4	Planktonic Cladocera PCA1	Planktonic Cladocera PCA2
0.04	0.31*	0.02	0.19	0.01	0.15
0.08	0.05	0.03	0.04	0.00	0.16
0.07	0.03	0.00	0.02	0.00	0.19
0.01	0.52**	0.04	0.30*	0.00	0.18
0.02	0.07	0.00	0.03	0.00	0.12
0.06	0.01	0.02	0.00	0.01	0.12
0.01	0.44**	0.11	0.52**	0.03	0.10
0.00	0.18	0.19	0.37*	0.02	0.00
0.01	0.11	0.19	0.23	0.02	0.00
0.00	0.53**	0.10	0.52**	0.01	0.16
0.03	0.28*	0.11	0.47**	0.02	0.04
0.00	0.16	0.15	0.27	0.01	0.05
0.21*	0.48**	0.05	0.32*	0.26*	0.06
0.11	0.14	0.30*	0.17	0.01	0.02
0.19*	0.12	0.22	0.20	0.01	0.02
0.33**	0.11	0.00	0.01	0.07	0.29*
0.29**	0.02	0.01	0.00	0.02	0.41**
0.34**	0.07	0.00	0.07	0.00	0.63**

have affected the catchment and hence the lake by causing changes e.g., in soil properties, vegetation cover and nutrient cycling. To test this possibility, we launched limnological investigations at the nearby Lake Masehjavri in order to assess the potential impacts of reindeer management on the water quality and lake characteristics. Masehjavri was specifically chosen, as it was thought to be particularly susceptible for such impacts, as it is small (0.2 km^2), shallow ($\approx$10 m) and directly affected by reindeer; the local reindeer herders carry out the yearly marking of reindeer in the vicinity of the lake which means that thousands of animals are gathered on its shores. However, the preliminary investigations have not succeeded in showing any changes either in the nutrient status or in the biological communities of the lake that could be connected with the reindeer (Linqvist et al., unpublished data).

Lake Saanajärvi is situated in a region which at present has one of the lowest deposition of atmospheric pollutants in Finland as well as in the whole north-west Europe. The lake is nevertheless subjected to atmospheric pollution related to fossil fuel compustion as shown by the SCP and soft IRM mineral magnetic data. The SCP profile shows typical features shown by SCP profiles throughout Europe. The concentration profile shows some irregularities probably due to the low concentrations. The SCP accumulation rate profile resolves some of these irregularities and suggests that the general pattern is additionally influenced by 'local' sources, probably from the Kola Peninsula.

There are clearly different mineral sources contributing to the mineral assemblage in different parts of the Saanajärvi core, but within the last 100 years the main effect is from low coercivity mineral source - probably multidomain 'magnetite' pollution particles. The evidence in the magnetic records (0–10 cm) for major influx events delivering detrital minerals to the lake bed is not strong, except possibly around 1860–1870 where high values of χ_{high} % suggest an input of Fe-bearing minerals. Stronger evidence exists for significant changes in detrital flux (intensity and source) in lower parts of the sediment sequence (not shown) that may correspond to the Little Ice Age period.

Magnetic records of pollution (generally considered to record particles derived from coal burning) from USA and UK (cf. Dearing, 1999) show initial rises in 1850 and peak values between 1950 and 1980 and this overall trend is observable at Saanajärvi. Some evidence for reduced pollution in the 1960's, followed by higher pollution in the 1970's, may demonstrate the effects of pollution controls and the effects of long-distance transport of particles from tall power station stacks.

In general, there is a good correspondance between the SCP data and the magnetic pollution signal at Lake Saanajärvi, suggesting that the lake has been subjected to long-distance transportation of atmospheric pollutants since the late 19th century. Whether this pollution has been effective enough to produce the observed changes in the sediment biota is however questionable. The pollution levels at Saanajärvi are extremely low in comparison with areas which show clear indications of pollution such as lake acidification. The present limnological data from lake Saanajärvi suggest that atmospheric deposition has nevertheless increased sulphur loading in the lake. The acid compounds are stored in the snow during winter and released in spring, causing a marked acid shock in the lake each spring, with the lakewater pH dropping transiently by 1–2 units (Sorvari et al., 2000). However, this acid meltwater pulse is very short in duration and does not produce any corresponding drop in lake alkalinity, suggesting that the watershed and in-lake alkalinity-generating processes are still effectively opposing acidification of this site. The marked stability in the reconstructed pH values, the unchanged concentrations of sediment S, and the fact that all the dominant diatom taxa in the post 1900 sediments are indicative of non-acidic, neutral waters (see Sorvari & Korhola, 1998) lead us to conclude that atmospheric fallout of acid substances cannot have been the driving force for the observed biological change. Further support to our conclusions are achieved from palaeolimnological data from lakes in northeastern Finnish Lapland that similarly suggest that no substantial changes in the acidification situation of the lakes have occurred despite the high local acid deposition from the emissions sources of the nearby smelter industry in Russia (Korhola et al., 1999).

There is also no evidence of atmospheric nutrient pollution either in the sedimentary deposits (in the form of e.g., eutrophication) or in the present limnology of the lake. The present nutrient status of the lake is extremely low, with PO_4-P lying under the detection limit, NO_3-N having a median of 30 µg l^{-1}, and a median for NH_4-N of 9 µg l^{-1}. The dominant diatom algal flora of the lake during the last century (e.g., *Cyclotella glomerata, C. comensis*) has been classified by Reynolds (1998a) as characteristic to ultra-oligotrophic lakes with strong deficiencies in nutrient supply.

A wide range of palaeoclimate evidence from lake sediments, tree-rings, glaciers, and marine sediments suggests that the northern high-latitude regions experienced a pronounced warming that started around 1840 and peaked in the mid-20th century (Overpeck et al., 1997). This warming marked the termination of the Little Ice Age in the area and has caused many changes in the Arctic geo-, cryo- and biosphere. On the basis of long meteorological data series from northern Sweden, Moberg and Alexandersson (1997) have shown that this general climate trend is identifiable in northern Fennoscandia as well. According to their observations, there was an increase of ca. 1–2 °C in mean annual temperatures, and an increase of approximately 1.5 °C in mean summer temperatures in northern Fennoscandia between the mid-1900 and 1930's. After the warm anomaly in the 1930's, temperatures remained relatively stable over the next few decades, but have cooled slightly since the 1950's. During the last few decades, spring temperatures have generally increased, whereas late-summer and autumn temperatures have slightly decreased (Tuomenvirta & Heino, 1986). These climate features, i.e., a rise in mean temperatures starting from ca. 1850, a distinct peak in 1930's, and a slight cooling trend since then, can also be identified in the long-term instrumental series, historical records of ice cover and tree ring measurements from Finnish Lapland (Sorvari et al., 2002) as well as in the mean annual temperature records (Figure 9) specifically reconstructed for Saanajärvi in the frame of the MOLAR project (Agustí-Panareda & Thompson, this issue).

Changes in regional climate, as documented in instrumental and reconstructed meteorological records, are remarkably well correlated to the biological and lithological records in the sediments of Lake Saanajärvi (Figure 9). The most pronounced change in the sediment record that occurred around the turn of the 20th century was synchronous with the above described post-Little Ice Age warming, suggesting a profound climate impact on the ecosystem of Lake Saanajärvi during the last hundred years.

With a warming climate, there is a general tendency for lake water temperatures to become warmer (Schindler et al., 1996). This, is turn, will increase the density difference between surface and bottom waters, and thus affect lake stratification. As a consequence of climate warming, stratification in dimictic lakes usually becomes stronger and shallower (DeStasio et al., 1996), whereas previously isothermic (monomictic) lakes may become stratified in summer (Schindler, 1997). According to simulation studies by Hondzo and Stefan (1993), future global warming (the 2×CO_2 scenario) could result in a lengthening of the period of summer stratification by more than a month in deep and medium-deep lakes. Similar type of results have been obtained in model studies of some Finnish lakes of different sizes (Huttula et al., 1992). These models generally suggest 5–6 °C higher epilimnion temperatures and considerably steeper thermoclines in the new situation (the 2×CO_2 scenario). For example, in Lake Lappajärvi, which was the largest (161 km^2) lake included in the simulation study of Huttula et al. (1992), the thermocline is predicted to be about 5–8 m higher and the summer stratification period about one month longer under altered conditions created by the doubling CO_2.

The chemical and biological status of lakes is usually strongly related to these climate-induced physical properties of the water column, with the relative length of water column stratification and mixing periods having a particularly great importance (Imboden & Wüest, 1995). Many recent studies (e.g., George & Taylor, 1995; Gaedke et al., 1998; Reynolds, 1998b) demonstrate a clear relationship between the timing and intensity of stratification and the seasonal dynamics of phyto- and zooplankton in different kinds of water bodies. For example, in Lake Constance, Switzerland, the growth of dominant algae was found to be markedly determined by the 'effective light climate' (i.e., the average light intensity in the mixed water layer), which, in turn, was significantly controlled by the extent of thermal stratification (Sommer, 1983). A six-years long monitoring study (Gaedke et al., 1998) of the same lake further revealed that vernal blooms of algae never occurred before the algae were largely safe from being mixed with the deeper (> 20 m) water column, providing evidence in support of the general concept that the phytoplankton spring growth depends on thermal stability of the water column in deep temperate lakes. In Lake Windermere (UK), George and Taylor (1995) showed that the average summer biomass of zooplankton was similarly affected by the lake stratification patterns. The effect was mainly mediated by changes in the food web, as the edible algae showed growth dynamics largely influenced by the development of thermal stratification. These results, along with many other studies, suggest that plankton succession in lakes may be significantly controlled by thermal stratification and other climate-related lake physical factors.

Lake Saanajärvi is currently thermally stratified for a few weeks in summer, with the thermocline depth lying at depths of 4–6 m in early summer, 6–8 m in mid-summer, and 8–10 m before autumnal overturn (Sorvari et al., 2000). This is in contrast with most other lakes in the area, which, owing to their clear water and shallow depth, usually do not develop clear stratification during summer. For example, we found 42 of the 53 tree-line lakes sampled in years 1994–95 for limnological characteristics to be thermally unstratified during the mid-summer sampling period (Korhola et al., 2002). Most of these unstratified northern lakes also lack a true plankton. In addition to Lake Saanajärvi, we have monitored two other near-by lakes more intensively for limnological features. Tsahkaljarvi, an 18 m deep humic, brown-coloured lake, does stratify in summer while Masehjärvi, Z_{max} = 11 m, does not. No clear phytoplankton maximum occurs in the latter lake. Because stratification seems to be a crucial factor for lake dynamics in the region, any changes in its duration, depth, stability or strength might have far-reaching impacts for the whole functioning of a freshwater ecosystem.

In Saanajärvi, epilimnetic water temperatures tend to vary closely, albeit with a time lag of about 15 d with air temperature, as shown by the meteorological data derived from the automatic weather station installed 1 August 1996 on the south-eastern shore of the lake (Livingstone et al., unpublished data). It is, therefore, legitimate to assume that the post-Little Ice Age climatic warming between AD 1850 and 1930 resulted in higher surface-water temperatures and hence longer and stronger summer stratification at Saanajärvi. By taking into account that most of the Arctic, including northern Fennoscandia, experienced a pronounced cooling with coldest temperatures of the entire Little Ice Age in the first part of the 19th century (Moberg & Alexandersson, 1997; Overpeck et al., 1997), it may even be possible that Lake Saanajärvi changed from a cold monomictic to the present-day dimictic lake during the subsequent climate warming; however, this conclusion needs to be tested by proper modelling of lake physics.

In any case, the steeper thermocline can be assumed to have promoted the growth of plankton at Saanajärvi both mechanically and via changes in nutrient availability. In general, the depth distribution of algal populations is known to be controlled for a large part by the extent of thermal stratification (Sommer, 1983). With a stronger thermocline and increased thermal stability, more turbulent conditions were created in the upper water layer of Lake Saanajärvi, which favoured the emergence of a planktonic component; many planktonic algae, particularly centric diatoms, are denser than water and require a degree of turbulence to be kept in suspension (Heaney et al., 1996). However, the present phytoplankton maximum at Lake Saanajärvi occurs during the mixing period in autumn, when the dominant planktonic diatoms also reach their highest abundances (Sorvari et al., 2000). This autumnal production maximum is primarily maintained by the nutrient dynamics. During the summer stabilisation, nutrients (e.g., NO_3-N; NH_4-N) are concentrated in the lower denser water column, from where they are released for the utilisation of primary producers as the stratification situation breaks down each autumn (Rautio et al., 2000; see also Gaedke et al., 1998, Catalan et al., this issue (b)). On the basis of the multi-proxy data available from sediments of Lake Saanajärvi it is assumed that this situation of permanent and strong summer stratification (and resulting changes in lake dynamics) was created in the lake only after the major climatic warming since the termination of the Little Ice Age.

Although we think that the increased duration and steepening of thermal stratification was the main driving force behind the observed changes in the palaeobiology of the lake, other factors may also have contributed to the changes observed in species compositions and sediment features. For instance, length of ice-cover period, duration of growing season, light penetration, oxygen consumption, and rate of chemical weathering are all factors that are at least partially climate-driven and changes in them could also have affected the lake dynamics. Nevertheless, the coherence of our results and interpretations with the implications from corresponding palaeolimnological studies from elsewhere in Lapland (Sorvari et al., 2002) and in the Arctic regions (Douglas et al., 1994; Gajewski et al., 1997; Overpeck et al., 1997) strongly support the idea that even relatively minor changes in regional climate can result in substantial changes in functioning of lakes. In the case of Lake Saanajärvi, it is a challenging task for future studies to find out whether earlier climatic events during the Holocene have managed to produce similar kind of traces in the lake sediment record. These longer-term studies will, hopefully, also help us to ultimately assess which part of the recent change is caused by natural processes and how much of it can be explained by anthropogenic influence, including the pollution effects.

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References

Agustí-Panareda, A. & R. Thompson, 2002. Reconstructing air temperature at eleven remote alpine and arctic lakes in Europe from 1781 to 1997 AD. J. Paleolim. 28: 7–23.

Appleby, P. G., P. J. Nolan, D. W. Gifford, M. J. Godfrey, F. Oldfield, N. J. Anderson & R. W. Battarbee, 1986. ^{210}Pb dating by low background gamma counting. Hydrobiologia 141: 21–27.

Appleby, P. G., N. Richardson & P. J. Nolan, 1992. Self-absorption corrections for well-type germanium detectors. Nucl. Inst. Meth. B71: 2

Battarbee, R. W., R. Thompson, J. Catalan, J.-A. Grytnes & H. J. B. Birks, 2002a. Climate variability and ecosystem dynamics of remote alpine and arctic lakes: the MOLAR project. J. Paleolim. 28: 1–6.

Battarbee, R. W., J-A. Grytnes, R. Thompson, P. G. Appleby, J. Catalan, A. Korhola, H. J. B. Birks, E. Heegaard & A. Lami, 2002b. Comparing paleolimnological and instrumental evidence of climate change for remote mountain lakes over the last 200 years. J. Paleolim. 28: 161–179.

Blom, T., A. Korhola & J. Weckström, 1998. Physical and chemical characterisation of small subarctic lakes in Finnish Lapland with special reference to climate change scenarios. In Lemmelä, R. & Helenius, N. (eds), Proceedings of The Second International Conference on Climate and Water, Espoo, Finland, 17–20 August 1998, 576–587.

Blom, T., A. Korhola, J. Weckström, T. Laing, J. Snyder, G. M. MacDonald & J. P. Smol, 2000. Physical and chemical characterisation of small subarctic headwater lakes in Finnish Lapland and the Kola Peninsula. Verh. Int. Verein. Limnol. 27: 316–320.

Camburn, K. E. & J. C. Kingston, 1986. The genus *Melosira* from soft-water lakes with special reference to northern Michigan, Wisconsin and Minnesota. In Smol, J. P., R. W. Battarbee, R. B. Davis & J. Meriläinen (eds), Diatoms and Lake Acidity. Dordrecht: Dr W. Junk Publishers, 17–35.

Cameron, N. G., H. J. B. Birks, V. J. Jones, F. Berge, J. Catalan, R. J. Flower, J. Garcia, B. Kawecka, K. A. Koinig, A. Marchetto, P. Sánchez-Castillo, R. Schmidt, M. Šiško, N. Solovieva, E. Štefková & M. Toro, 1999. Surface-sediment and epilithic diatom pH calibration sets for remote European mountain lakes (AL:PE Project) and their comparison with the Surface Waters Acidification Programme (SWAP) calibration set. J. Paleolim. 22: 291–317.

Dearing, J. A., J. F. Boyle, P. G. Appleby, A. W. Mackay & R. J. Flower, 1998. Magnetic properties of recent sediments in Lake Baikal, Siberia. J. Paleolim. 20: 163–173.

Dearing, J. A., 1999. Holocene environmental change from magnetic proxies in lake sediments. In Maher, B. A. & R. Thompson (eds), Quaternary Climates and Magnetism, Cambridge University Press, 231–278.

DeStasio, B. T., J. M. Hill, N. P. Kleinhans, N. P. Nibbelink & J. J. Magnuson, 1996. Potential effects of global climate change on small north temperate lakes: physics, fish and plankton. Limnol. Oceanogr. 41: 1136–1149.

Douglas, M. S. V., J. P. Smol &. W. Blake Jr., 1994. Marked post-18th century environmental change in high-arctic ecosystems. Science 266: 416–419.

Duff, K. E., B. A. Zeeb, J. P. Smol & J. R. Glew, 1994. Atlas of Chrysophycean Cysts. Kluwer Academic Publishers, Dordrecht, 200 pp.

Gaedke, U., R. D. Ollinger, P. Kirner & E. Bäuerle, 1998. The influence of weather conditions on the seasonal plankton development in a large and deep lake (L. Constance). III. The impact of water column stability on spring algal development. In George, D. G. et al. (eds), Management of Lakes and Reservoirs During Global Climate Change. Kluwer Academic Publishers, Netherlands, 71–84.

Gajewski, K., P. B. Hamilton & R. McNeely, 1997. A high resolution proxy-climate record from an arctic lake with annually-laminated sediments on Devon Island, Nunavut, Canada. J. Paleolim. 17: 215–225.

George, D. G. & A. H. Taylor, 1995. UK lake plankton and the Gulf Stream. Nature 378: 139.

Guilizzoni, P., G. Bonomi, G. Galanti & D. Ruggiu, 1983. Relationship between sedimentary pigments and primary production: evidence from core analyses of twelve Italian lakes. Hydrobiologia 103: 103–106.

Heaney, S. I., J. E. Parker, C. Butterwick & K. J. Clarke, 1996. Interannual variability of algal populations and their influence on lake metabolism. Freshwat. Biol. 35: 561–577.

Hondzo, M. & H. G. Stefan, 1993. Regional water temperature characteristics of lakes subjected to climate change. Clim. Change 24: 187–211.

Houghton, J. J., L. G. Meiro Filho, B. A. Callender, N. Harris, A. Kattenberg & K. Maskell (eds), 1996. Climate Change 1995 – The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, Cambridge University Press, 572 pp.

Huttula, T., A. Peltonen, Ä. Bilaletdin & M. Saura, 1992. The effects of climatic change on lake ice and water temperature. Aqua Fennica 22: 129–142.

Imboden, D. M. & A. Wüest, 1995. Mixing mechanisms in lakes. In Physics and Chemistry of Lakes. Springer.

Järvinen, A., 1987. Basic climatological data on the Kilpisjärvi area, NW Finnish Lapland. Kilpisjärvi Notes 10: 1–16.

Korhola, A., 1999. Distribution patterns of Cladocera in subarctic Fennoscandian lakes and their potential in environmental reconstruction. Ecography 22: 357–373.

Korhola, A., J. Weckström & M. Nyman, 1999. Predicting the long-term acidification trends in small subarctic lakes using diatoms. J. Appl. Ecol. 36: 1021–1034.

Korhola, A., J. Weckström, L. Holmström & P. Erästö, 2000. A quantitative Holocene climatic record from diatoms in northern Fennoscandia. Quat. Res. 54: 284–294.

Korhola, A., J. Weckström & T. Blom, 2002. Relationships between lake and land-cover features along latitudinal vegetation ecotones in arctic Fennoscandia. Arch. Hydrobiol. Suppl. 139/2, Monograph Studies, pp. 203–235.

Krammer, K. & H. Lange-Bertalot, 1986–1991. Bacillariophyceae. In Ettl, H., J. Gerloff, H. Heynig & D. Mollenhauer (eds), Süßwasserflora von Mitteleuropa, Vol. 2 (1–4). Stuttgart/Jena: Gustav Fischer Verlag.

Lami, A., P. Guilizzoni & A. Marchetto, 2000. High resolution analysis of fossil pigments, carbon, nitrogen and sulphur in the sediment of eight European Alpine lakes: the MOLAR project. J. Limnol. 59: 15–28.

Lange-Bertalot, H. & D. Metzeltin, 1996. Indicators of Oligotrophy. 800 taxa representative of three ecologically distinct lake types. In Lange-Bertalot (ed.), Iconographia Diatomologica. Annotated Diatom Micrographs, 2nd ed. Koelz Scientific Books, 390 pp.

Lotter, A. F., H. J. B. Birks, W. Hofmann & A. Marchetto, 1997. Modern diatom, cladocera, chironomid, and chrysophyte cyst assemblages as quantitative indicators for the reconstruction of past environmental conditions in the Alps. I. Climate. J. Paleolim. 18: 395–420.

Moberg, A. & H. Alexandersson, 1997. Homogenization of Swedish temperature data. Part II: homogenized gridded air temperature compared with a subset of global gridded air temperature since 1861. Int. J. Clim. 17: 35–54.

Mölder, K. & R. Tynni, 1967–1973. Über Finnlands rezente und subfossile Diatomeen. Bull. Geol. Soc. Fin. Vols 39: 199–217, 40: 151–170, 41: 235–251, 42: 129–144, 43: 203–220, 44: 141–149, 45: 159–179.

Norton, S. A., A. Henriksen, P. G. Appleby, L. L. Ludwig, D. V. Vereault & T. S. Traaen, 1992. Trace metal pollution in eastern Finmark, Norway, as evidenced by studies of lake sediments. Report 487/92. Norwegian Institute for Water Research. Oslo.

Olander, H., H. J. B. Birks, A. Korhola & T. Blom, 1999. An expanded calibration model for inferring lakewater and air temperatures from fossil chironomid assemblages in northern Fennoscandia. The Holocene 9: 279–294.

Overpeck, J, K., D. Hughen, R. Hardy, R. Bradley, M. Case, M. Douglas, B. Finney, K. Gajewski, G. Jacoby, A. Jennings, S. Lamoureux, A. Lasca, G. MacDonald, J. Moore, M. Retelle, S. Smith, A. Wolfe & G. Zielinski, 1997. Arctic environmental change of the last four centuries. Science 278: 1251–1256.

Psenner, R. & R. Schmidt, 1992. Climate-driven pH control of remote alpine lakes and effects of acid deposition. Nature 356: 781–783.

Rautio, M., S. Sorvari & A. Korhola, 2000. Diatom and crustacean zooplankton communities, their seasonal variability and representation in the sediments of subarctic Lake Saanajärvi. J. Limnol 59: 81–96.

Reynolds, C. S., 1998a. What factors influence the species composition of phytoplankton in lakes of different trophic status? Hydrobiologia 369/379: 11–26.

Reynolds, C. S., 1998b. Linkages between atmospheric weather and the dynamics of limnetic phytoplankton. In George, D. G. et al. (eds), Management of Lakes and Reservoirs during Global Climate Change. Kluwer Academic Publishers, Netherlands.

Rose, N. L., 1994. A note on further refinements to a procedure for the extraction of carbonaceous fly-ash particles from sediments. J. Paleolim. 11: 201–204.

Rose, N. L., 1995. Carbonaceous particle record in lake sediments from the Arctic and other remote areas of the northern hemisphere. Sci. Tot. Env. 160/161: 487–496.

Rose, N. L., S. Harlock & P. G. Appleby, 1999. The spatial and temporal distributions of spheroidal carbonaceous fly-ash particles (SCP) in the sediment records of European mountain lakes. Water Air Soil Pollut. 113: 1–32.

Rose, N. L., C. L. Rose, J. F. Boyle & P. G. Appleby, in press. The spatial and temporal distribution of atmospherically deposited pollutants on Svalbard as recorded by lake sediments. J. Paleolim.

Rouse, W. R., M. S. V. Douglas, R. E. Hecky, A. E. Hershey, G. W. Kling, L. Lesack, P. Marsh, M. MacDonald, B. J. Nicholson, N. T. Roulet & J. P. Smol, 1997. Effects of climate change on the freshwaters of arctic and subarctic North America. In Cushing, C. E. (ed.), Freshwater Ecosystems and Climate Change in North America. John Wiley & Sons, Chichester, 55–84.

Schindler, D. W., 1997. Widespread effects of climatic warming on freshwater ecosystems in North America. In Cushing, C. E. (ed.), Freshwater Ecosystems and Climate Change in North America. John Wiley & Sons, Chichester, 225–249.

Schindler, D. W., S. E. Bayley, B. R. Parker, K. G. Beaty, D. R. Cruikshank, E. J. Fee, E. U. Schindler & M. P. Stainton, 1996. The effects of climatic warming on the properties of boreal lakes and streams at the Experimental Lake Area, northwestern Ontario. Limnol. Oceanogr. 41: 1004–1017.

Smol, J. P., I. R. Walker & P. R. Leavitt, 1991. Paleolimnology and hindcasting climatic trends. Verh. Int. Ver. Limnol. 24: 1240–1246.

Sommer, U., 1983. Light, stratification and zooplankton as controlling factors for the spring development of phytoplankton in Lake Constance. Schweiz Hydrol. 45: 394–404.

Sorvari, S. & A. Korhola, 1998. Recent diatom assemblage changes in subarctic Lake Saanajärvi, NW Finnish Lapland, and their palaeoenvironmental implications. J. Paleolim. 20: 205–215.

Sorvari, S., M. Rautio & A. Korhola, 2000. Seasonal dynamics of subarctic Lake Saanajärvi in Finnish Lapland. Verh. Int. Verein. Limnol. 27: 507–512.

Sorvari, S., A. Korhola & R. Thompson, 2002. Lake diatom response to recent Arctic warming in Finnish Lapland. Glob. Change Biol. 8: 153–163.

Thompson, R. & F. Oldfield, 1986. Environmental Magnetism, Allen and Unwin, London.

Thompson, R. & R. M. Clark, 1993. Quantitative marine sediment core matching using a modified sequence-slotting algorithm. In Hailwood, E. A. & R. B. Kidd (eds), High Resolution Stratigraphy. J. Geol. Soc. Lond. Spec. Publ. No. 70: 39–49.

Tuomenvirta, H. & R. Heino, 1996. Climatic changes in Finland – recent findings. Geophysica 32: 61–75.

Tynni, R., 1975–1980. Über Finnlands rezente und subfossile Diatomeen. Geol. Surv. Fin. Bull. Vols 274: 1–55, 284: 1–37, 296: 1–55, 312: 1–93.

Vincent, W. F. & R. Pienitz, 1997. Sensitivity of high-latitude freshwater ecosystems to global change: temperature and solar ultraviolet radiation. Geosci. Canada 23: 231–236.

Walden, J., F. Oldfield & J. P. Smith (eds), 1999. Environmental Magnetism: a practical guide. Technical Guide, No. 6. Quat. Res. Assoc., London, pp. 185–196.

Weckström J., A. Korhola & T. Blom, 1997a. The relationship between diatoms and water temperature in thirty subarctic Fennoscandian lakes. Arc. Alp. Res. 29: 75–92.

Weckström, J., A. Korhola & T. Blom, 1997b. Diatoms as quantitative indicators of pH and water temperature in subarctic Fennoscandian lakes. Hydrobiologia 347: 171–184.

Wik, M. & I. Renberg, 1991. Recent atmospheric deposition in Sweden of carbonaceous particles from fossil fuel combustion surveyed using lake sediments. Ambio 20: 289–292.

Züllig, H., 1982. Untersuchungen über die Stratigraphie von Carotinoiden im geschichteten Sediment von 10 Schweizer Seen zur Erkundung früherer Phytoplankton-Entfaltungen. Schweiz. Z. Hydrol. 44: 1–98.