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High-resolution analyses of recent sediments from a Norwegian mountain lake and comparison with instrumental records of climate

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Abstract

The purpose of the palaeolimnological research project carried out at Øvre Neådalsvatn was to apply a number of physical and biological proxy-climate analyses to recent sediments and to compare the results of these analyses with instrumental records of climate. Using a radiometric chronology to match the sediment core with the calendar ages of the reconstructed instrumental record, and by time-averaging the instrumental record, the statistical significance of the relationships between each of the sediment-climate proxies and the reconstructed instrumental-climate measurements were evaluated.

Acid deposition at Øvre Neådalsvatn has been low and its impact limited. Whilst there has been an overall rise in mean annual temperature of about 1 °C since 1900, the physical and biological sediment records studied appear to be insensitive to climate warming of this magnitude. On the one hand, this may be a result of the loss in temporal resolution caused by time-averaging the instrumental data; on the other hand, the lake may be insensitive to the impact of this climate change.

This is the sixth of 11 papers published in this special issue on the palaeolimnology of remote mountain lakes in Europe resulting from the MOLAR project funded by the European Union. The guest editor was Richard W. Battarbee.

Introduction

The aims of the MOLAR project are set out in the introductory paper of this issue (Battarbee et al., 2002a, this issue). Previous palaeolimnological research at Øvre Neådalsvatn has focused on the lake as a relatively unpolluted reference site in a study of the effects of the atmospheric deposition of pollutants across mountain ranges in Europe (Cameron et al., 1993; Wathne et al., 1997). Although Øvre Neådalsvatn was found to be a relatively unpolluted site with, for example, little impact of acid deposition on the biota, the records of pollution indicators such as spheroidal carbonaceous particles (SCP) show that the lake was subject to a low level of acid deposition beginning approximately 50–60 years ago and rising more rapidly from about 1979 to the 1990's (Cameron et al., 1993). The lake is susceptible to acid deposition, with a lakewater Ca concentration of about 20 μeq l^{-1}. However, stability of the dominant diatom and chironomid communities is evidence for a low level of pollution impact. In addition a survey and monitoring of the lake's contemporary biology showed that there is a reproducing brown trout population apparently unaffected by acid deposition.

Given the relatively unpolluted state of Øvre Neådalsvatn compared with lakes in mountain regions elsewhere in Europe, the site was selected as an excellent lake at which to explore the potential of palaeolimnological proxies as climate indicators. Some further SCP work was pursued at the site to establish the pollution history of the lake and for comparison with other lakes within the MOLAR project.

Study site

Øvre Neådalsvatn lies in the northern part of the Norwegian Mountains (62° 46′ 30″N, 09° 00′E) at an altitude of 728 m a.s.l. The lake morphometry is summarised in Table 1. The catchment consists of gneiss overlain with alpine soils. Alpine heath vegetation predominates, but there is a significant proportion of bare rock. Parts of the catchment are grazed at low intensity during the summer months.

Monitoring of the weather at the lake was carried out using an automatic weather station (AWS). From 18–21 July 1998, measurements of air temperature, incident solar radiation, net radiation, relative humidity, precipitation, wind speed and wind direction were made every 30 min at a height of about 8.5 m above the surface of Øvre Neådalsvatn using an Aanderaa 2700 AWS located about 20 m south-west of the lake outflow. Data obtained from the AWS give an indication of the seasonal variability in the local weather conditions prevailing at the lake.

Table 1. Øvre Neådalsvatn, lake size characteristics

Surface area	50 ha
Catchment area	16 km^2
Maximum depth	18 m
Mean depth	3.9 m
Volume	1.95×10^6 m^3

Daily mean air temperatures at Øvre Neådalsvatn are below or close to 0 °C during about 6 months of the year (November–March). Unfortunately, for technical reasons air temperatures below –3.9 °C were not measured. However, the daily mean air temperature exceeded 0 °C during at least part of each month of the year, so extremely cold conditions are unlikely to persist for longer than a week or two. The maximum daily mean air temperature recorded during the period of observation was 20.2 °C.

During the sampling period, Øvre Neådalsvatn was observed to have been ice-covered during about 8 months of the year (November–June). Observations are also available from previous years: break-up is known to have occurred on 6 July 1994, 16 July 1995, 28 June 1996, 17 July 1997 and between 28 June 1998 and 1 July 1998; freeze-up is known to have occurred approximately on 1 November 1994 and 25 October 1997.

The main effect of local topography on the solar radiation incident on Øvre Neådalsvatn occurs in the middle of the period of ice-cover, so that local topography is unlikely to have a significant effect on either freezing or thawing processes. Synoptic-scale climate integrated over several weeks probably governs the timing of freeze-up and break-up on this lake (cf. Palecki & Barry, 1986). The timing of freeze-up is thus likely to reflect the air temperatures prevailing at the lake during October, and the timing of break-up those prevailing during June. The influence of climatic forcing on the ecology of Øvre Neådalsvatn may therefore be largely indirect (i.e., via ice cover).

Based on 2 years of thermistor data, the surface water temperature of Øvre Neådalsvatn exceeds 1 °C during 39% of the year, and exceeds 4 °C during 25% of the year. This implies that the open-water period lasts approximately 135 days (4.4 months), and the stratified period 92 days (3.0 months).

Because of the large heat capacity of water, coupled with the lag involved in the downward mixing of heat, lakes tend to act as integrators of climatic forcing. Because of this, surface water temperatures react to this forcing more sluggishly than air temperatures. In the case of Øvre Neådalsvatn, it was possible to model the water temperature during the open-water phase empirically as the mean of the previous 10 days air temperature. This simple approach accounted for both the smoothing of the high-frequency fluctuations that are present in air temperature but not in water temperature, and for the (relatively short) time lag of about 5 days that exists between air and water temperatures in the case of this particular lake.

Methods

Using a gravity corer (Glew, 1989), six new sediment cores 30–37 cm long were taken in September 1996 from the deepest point of the lake. The primary cores, designated ØVNE4 to ØVNE9, were extruded on site using sampling intervals of between 0.5 and 2 mm. This paper is concerned with the results of the analyses of cores ØVNE4, ØVNE5, ØVNE6 and ØVNE7 (Table 2).

Wet densities were measured by filling a 2 cm^3 weighed brass vial with a subsample of homogenised sediment. Dry weights were determined by placing 1–2 g of wet sediment in a weighed crucible and drying overnight to constant weight at 105 °C. Loss on ignition was measured after placing the crucible in a muffle furnace at 550 °C for 2 h. Crucibles were cooled in a desiccator before reweighing.

Samples from the cores ØVNE4 and ØVNE7 were analysed for ^{210}Pb, ^{226}Ra and ^{137}Cs by direct gamma assay in the Liverpool University Environmental Radioactivity Laboratory, using Ortec HPGe GWL series well-type coaxial low background intrinsic germanium detectors (Appleby et al., 1986). ^{210}Pb was determined via its gamma emissions at 46.5 keV, and ^{226}Ra by the 295 and 352 keV γ-rays emitted by its daughter isotope ^{214}Pb following 3 weeks storage in sealed containers to allow radioactive equilibration. ^{137}Cs was measured by its emissions at 662 keV. The absolute efficiencies of the detectors were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self-absorption of low energy γ-rays within the sample (Appleby et al., 1992).

Room temperature magnetic measurements were made on pre-weighed, freeze-dried, contiguous samples from core ØVNE7. Samples were placed in plastic film and measured using a vibrating sample magnetometer, pulse magnetisers and spinner magnetometer. This procedure provided continuous measurements of magnetisation in fields 0-1T and remanence measurements following fields of 1T, –20 mT and –300 mT with calculation (cf. Thompson & Oldfield, 1986; Dearing et al., 1998; Walden et al., 1999) of the following parameters: VSM, mass specific susceptibility (χ_{low}), mass specific and per cent ferrimagnetic susceptibility (χ_{ferri}; χ_{ferri} %), mass specific and per cent paramagnetic susceptibility (χ_{para}; χ_{para} %), mass specific saturation magnetisation (M_s), ratio saturation remanence:susceptibility (M_{rs}/χ_{low}), ratio saturation remanence:saturation magnetisation (M_{rs}/M_s) and coercive force (H_c). Spinner magnetometer: mass specific saturation remanent

Table 2. Sediment cores taken from Øvre Neådalsvatn for the MOLAR project and outline of the sampling and analyses carried out on each sediment sequence

Core	Extrusion interval	Number of samples	Analyses
ØVNE4	0–37.2 cm @ 2 mm	186	1) DW, LOI 2) Diatoms 3) Chrysophytes 4) SCP 5) ^{210}Pb dating
ØVNE5	0–28.6 cm @ 2mm	143	1) DW, LOI 2) Pigments 3) Grain size 4) Cladocerans
ØVNE6	0–35.4 cm @ 2mm	177	1) DW, LOI 2) Chironomids
ØVNE7	0–5 cm @ 2mm	82	1) DW, LOI
	5— 33.5cm @ 5mm	82	1) DW, LOI 2) ^{210}Pb dating 3) Mineral magnetics

magnetisation (SIRM), mass specific and per cent soft (–20 mT) remanence (soft IRM, soft IRM %), mass specific and per cent hard (–300 mT) remanence (HIRM, HIRM %), coercivity of remanence (H_{cr}).

Spheroidal Carbonaceous Particle (SCP) analysis followed the method described in Rose (1994). Dried sediment was subjected to sequential chemical attack by mineral acids to remove unwanted fractions leaving carbonaceous material and a few persistent minerals. SCPs are composed mostly of elemental carbon and are chemically robust. The use of concentrated nitric acid (to remove organic material), hydrofluoric acid (siliceous material) and hydrochloric acid (carbonates and bicarbonates) therefore does them no damage. A known fraction of the resulting suspension was evaporated onto a cover slip and mounted onto a microscope slide. The number of SCP on the cover slip 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}.

Preparation and counting of diatoms from sediment cores followed standard procedures (Battarbee, 1986). Cleaned diatoms were identified and counted under oil immersion at 1000× or 1200× magnification under phase contrast illumination. Diatom cell concentrations were determined using the microsphere method of Battarbee and Kneen (1982); for the core samples 500–600 valves were counted per sample. Identification of diatoms was aided by the use of a comprehensive collection of flora and taxonomic papers lodged at the Environmental Change Research Centre (ECRC), UCL.

Sample and slide preparation for chrysophyte stomatocyst analysis followed similar procedures to those used for the preparation of diatoms. However, microspheres were not added to the cleaned preparations. Cysts were analysed under the light microscope at a magnification of ×1200 using a combination of brightfield, phase contrast and differential interference contrast illumination. Counting was carried out on contiguous 2 mm samples to a depth of 56 mm, covering the period for which high quality instrumental climate data are available from 1781 AD to the present. The counting sum was 60–100 cysts per sample. An internal cyst taxonomy was used, based on the concepts presented in Duff et al. (1995). In some cases it was possible to match cysts with published taxa, however, with the exception of the 'stomatocyst 17', for the purposes of this analysis, an internal taxonomy of cyst types has been retained.

Diatom counts have been entered on the AMPHORA database at the ECRC. Data were analysed using a number of standard palaeoecological programs and packages on an IBM-compatible PC. pH reconstructions were carried out using the AL:PE calibration set (Cameron et al., 1999).

Chironomid analyses were performed on the core ØVNE6, sectioned at 2 mm intervals. The core chronology was produced by cross correlation of the lithostratigraphy of ØVNE6 with that of the dated core ØVNE4.

Fresh sediments were not treated with chemicals prior to sorting chironomid remains. Samples were carefully washed in water and sieved through a 100 µm mesh sieve. The head capsules were then picked out under a binocular microscope at 50× magnification, stored in 96% alcohol, and later mounted on a slide in Hoyer's solution for identification under the microscope. This is considered the best way to treat fragile subfossil remains. Most samples were not completely sorted, 120-150 head capsule remains were considered sufficient from each sediment interval.

Samples of approximately 1 cm^3 of dry homogenised sediment for Cladocera analysis were first heated for about half an hour in 150 ml 10% KOH. During heating a magnetic stirrer was used to speed up the deflocculation of the organic material, after which the solution was rinsed and sieved through 50 µm mesh to eliminate microparticles. The remaining sediment on the sieve was washed into a 15 ml tube, and 2–3 drops of safranin-glycerin solution were added to colour the Cladocera remains. Three slides were prepared from each sample by first homogenising the tube contents by shaking and then pipetting 200 µl of the sample onto an object glass, which was then covered with a 24 × 50 mm cover slip. Samples were examined using a Leitz LABORLUX 12 microscope at magnifications of 120–240×. All identifiable Cladocera exuviae were counted but only the most frequently recovered skeletal component for each taxon was used as an index of species abundance.

Pigments were extracted using the methods described by Lami et al. (1994, 2000) . Total pigments (chlorophylls and their derivatives, CD; crude carotenoids, TC) were measured spectrophotometrically and single specific carotenoids were measured using an HPLC system. Chlorophyll derivatives are expressed as spectrophotometric units per gram organic matter (U g OM^{-1}) (Guilizzoni et al., 1983). The total and the single carotenoids are expressed as mg g OM^{-1} and nmoles g LOI^{-1}, respectively (Züllig, 1985). Organic carbon and organic nitrogen were measured using a CHN analyser (Carlo Erba).

Details of the methods used in reconstructing climate parameters for particular lakes from instrumental climate data are given by Agustí-Panareda and Thompson (this issue). Sediment core parameters were regressed against reconstructed instrumental climate data using the best available sediment chronology and by smoothing the instrumental data to make it comparable with the sediment data. The transformation of sediment core and reconstructed instrumental data and the statistical significance testing techniques applied to the comparison of these data are described by Battarbee et al., 2002b, (this issue). The instrumental data were smoothed to match their resolution to that of the 2 mm core slices.

Results

Chronology

Radiometric dating was carried out on cores ØVNE4 and ØVNE7. The results of the radiometric analyses for ØVNE4 only are given in Table 3. Radiometric dates were calculated using either the CRS or CIC ^{210}Pb dating models (Appleby et al., 1978), following an assessment of which model was more appropriate.

Lead-210 results for the two new cores (ØVNE4 and ØVNE7) were very similar. Equilibrium of total ^{210}Pb activity with the supporting ^{226}Ra, corresponding to about 150 years accumulation, was reached at a depth of about 9 cm. ^{226}Ra activity was very uniform, with mean values of 73 Bq kg^{-1} in ØVNE4 and 72 Bq kg^{-1} in ØVNE7. Unsupported ^{210}Pb concentrations declined more or less exponentially with depth and at the same rate in both cores suggesting relatively uniform sediment accumulation rates throughout the past 150 years.

Table 3. ^{210}Pb chronologies for cores ØVNE4 & ØVNE7

	Sample depth cm	Date AD	Age yr	Error ±	Sediment accumulation rate cm yr^{-1}
ØVNE4	0.20	1994	2	1	0.079
	0.80	1985	11	1	0.067
	1.20	1979	17	1	0.056
	1.80	1968	28	2	0.059
	2.20	1962	34	2	0.062
	2.80	1952	44	2	0.057
	3.20	1945	51	3	0.055
	3.80	1934	62	3	0.059
	4.20	1927	69	3	0.063
	5.20	1912	84	4	0.060
	6.20	1894	102	5	0.054
	7.20	1875	121	5	0.050
	8.00	1859	137	6	0.049
ØVNE7	0.20	1994	2	1	0.084
	0.80	1986	10	1	0.078
	1.20	1981	15	1	0.070
	1.80	1972	24	2	0.065
	2.20	1966	30	2	0.066
	2.80	1957	39	2	0.069
	3.20	1951	45	2	0.068
	3.80	1942	54	3	0.065
	4.20	1936	60	3	0.063
	5.25	1919	77	3	0.062
	6.25	1902	94	4	0.053
	7.25	1881	115	5	0.047
	8.25	1860	136	5	0.044
	9.25	1835	161	7	0.042

The 1991 AL:PE core from this lake (ØVNE1) had high levels of ^{137}Cs activity in the surficial sediments originating in fallout from the 1986 Chernobyl accident. Maximum activities in the present cores still occur in the top 1 cm, though the values are just 65% of those in 1991. Since all three cores have very similar inventories, the diminution in the surficial values presumably reflects the combined effects of inputs of new sediment with lower ^{137}Cs activities and post-depositional mobility of ^{137}Cs within the sediment column. There is no clear record of either the 1986 or 1963 fallout maxima. ^{241}Am activities were below the limits of detection and did not provide an alternative chronology.

There was no significant difference between dates calculated using the CRS and CIC dating models. Both indicate more or less uniform accumulation throughout the past 150 years. Although there are a number of irregular fluctuations (some of which reflect the high standard errors in the calculations of this parameter), accumulation rates for the new cores ØVNE4 and ØVNE7 are similar to those for the earlier core ØVNE1 (Table 4).

Table 4. Mean sediment accumulation rates in Øvre Neådalsvatn since 1850

	1920–1990 g $cm^{-2} yr^{-1}$	1850–1990 g $cm^{-2} yr^{-1}$
ØVNE1	0.0097	0.0098 ± 0.0006
ØVNE4	0.0102	0.0100 ± 0.0004
ØVNE7	0.0101	0.0102 ± 0.0004

Mineral magnetic measurements

The main feature near the surface is a peak in all concentration parameters χ_{low}, χ_{ferri}, χ_{high}, M_s, M_{rs}, SIRM, SOFT IRM and to a lesser extent HIRM, which coincides in all cases at ~ 2.5 cm (Figure 1). Below this depth, values for SOFT IRM %, (Bo)cr are fairly constant, indicating a reasonably constant assemblage of ferrimagnetic and canted antiferromagnetic minerals. The key factors controlling the magnetic signal appear to be atmospheric pollution indicated by the presence of magnetosomes in the upper 5 cm of the core with detrital minerals below, shown by peaks in high coercivity material.

SCP analysis

SCP analysis was carried out in order to determine the level of atmospheric pollution at the lake and its potential effect on any sediment-climate record. Secondly the pattern of SCP concentrations down the core can be used to complement radiometric dating methods.

The SCP profile for ØVNE4 (Figure 2) is short with an SCP presence only in the uppermost 2.5 cm (1957 ± 2). This date agrees with the period usually corresponding to a rapid increase in SCP concentration across Europe and hence, as concentrations are low throughout the profile, may correspond to an increase in SCP concentration to above the detection limit, rather than the start of SCP deposition. In a core taken for the AL:PE project in 1991 (Rose et al., 1999), the ØVNE1 core showed a longer profile starting in the 1920's and

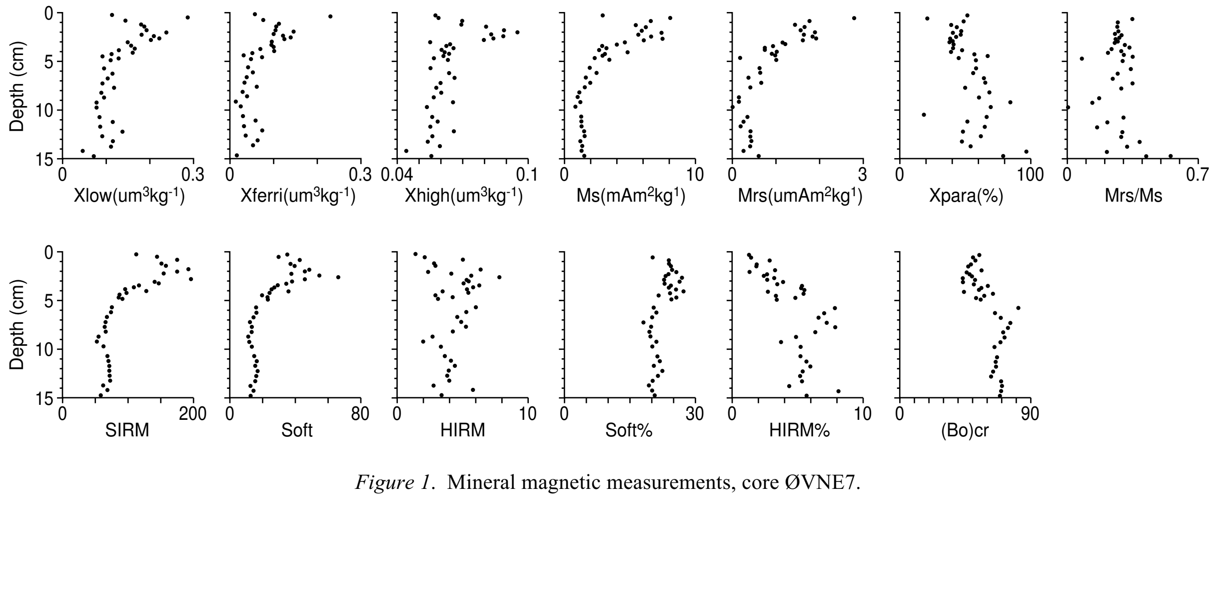

Figure 1. Mineral magnetic measurements, core ØVNE7.

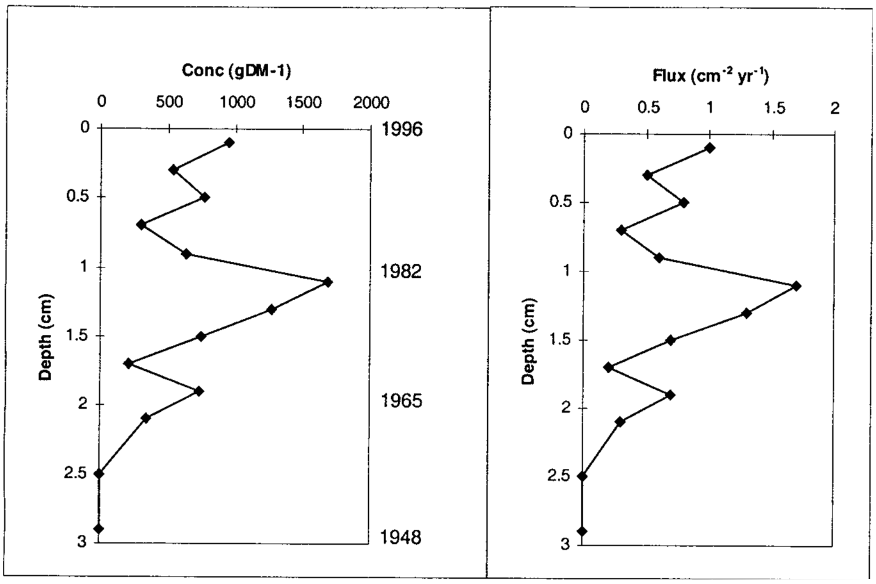

Figure 2. SCP concentrations and flux, core ØVNE4.

therefore supports this hypothesis. However, in this earlier core the rapid increase occurred in the 1980's. Although this is too late to correspond with the apparent increase to the detection limit in ØVNE4, it does correspond with a period of rapidly increasing SCP concentrations.

CNS and pigment analysis

The contents of N (about 0.5%) and C (about 10%) change little in the core. The C:N ratio is very regular at around 17–18 indicating a significant allochthonous component of organic matter. S concentrations are low (0.1–0.2%) and a slight increase is shown near to the core surface.

Total pigment concentrations are low; in particular the total carotenoids show the lowest concentrations. A steady increase of CD and TC is shown upwards from 7 and 3 cm respectively. A similar marked increase in the upper 3 cm of the core (not shown) is observed in myxoxanthophyll, fucoxanthin, and alloxanthin.

Diatom analysis and pH reconstruction

Diatom analysis was carried out on 60 contiguous samples taken at 2 mm intervals down to a depth of 12 cm

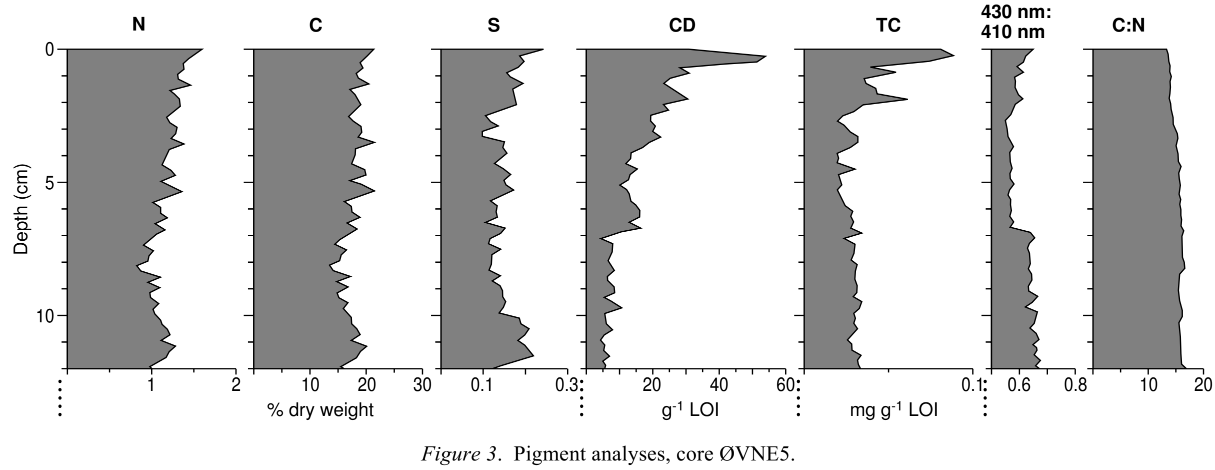

Figure 3. Pigment analyses, core ØVNE5.

in core ØVNE4. This depth represents the time period from 1781–1996, and is therefore appropriate for comparison with the reconstructed instrumental records of climate.

Diatom assemblages are diverse, and a total of 172 diatom taxa were identified in the sequence. Figure 4, which represents the abundances of species occurring at a minimum of over 5% in at least one sample, shows that the populations of dominant taxa are relatively stable with no marked changes in the abundance of common diatoms during the period of study.

The dominant diatoms in the core are all non-planktonic species and include a number of *Achnanthes* and *Aulacoseira* species typical of mountain lakes as well as other species typical of oligotrophic waters in general, such as *Cymbella perpusilla* and *Frustulia rhomboides* var. *saxonica*.

Diatom-based pH reconstruction (Figure 5) using the AL:PE training set (Cameron et al*.,* 1999) shows that there are only relatively small variations in reconstructed pH over the period covered by the core. After smoothing using a LOESS smoother, pH values vary between 5.9 and 6.1, and show only a slight overall decrease from 1781 to 1996.

Chrysophyte cyst analysis

A total of 81 chrysophyte stomatocyst taxa were identified. In the cyst percentage data, which are somewhat noisy, no significant long-term changes are apparent (Figure 6). The chrysophyte cyst assemblages are dominated by unornamented cysts with pores, in the size ranges of less than 5 µm and from 5–10 µm in diameter (cyst types A4 and A5, respectively). Cyst type A4 varies in abundance from c. 20–60% of the total assemblage, and type A5 comprises from c. 20–50% of the assemblage. These cyst taxa do not appear to show any consistent trends over the sequence.

A number of other cysts show restricted distributions or maxima in parts of the profile. For example E1 (cysts of < 5 µm with a collar and ornamented with spines) is absent from the samples at the base of the profile and

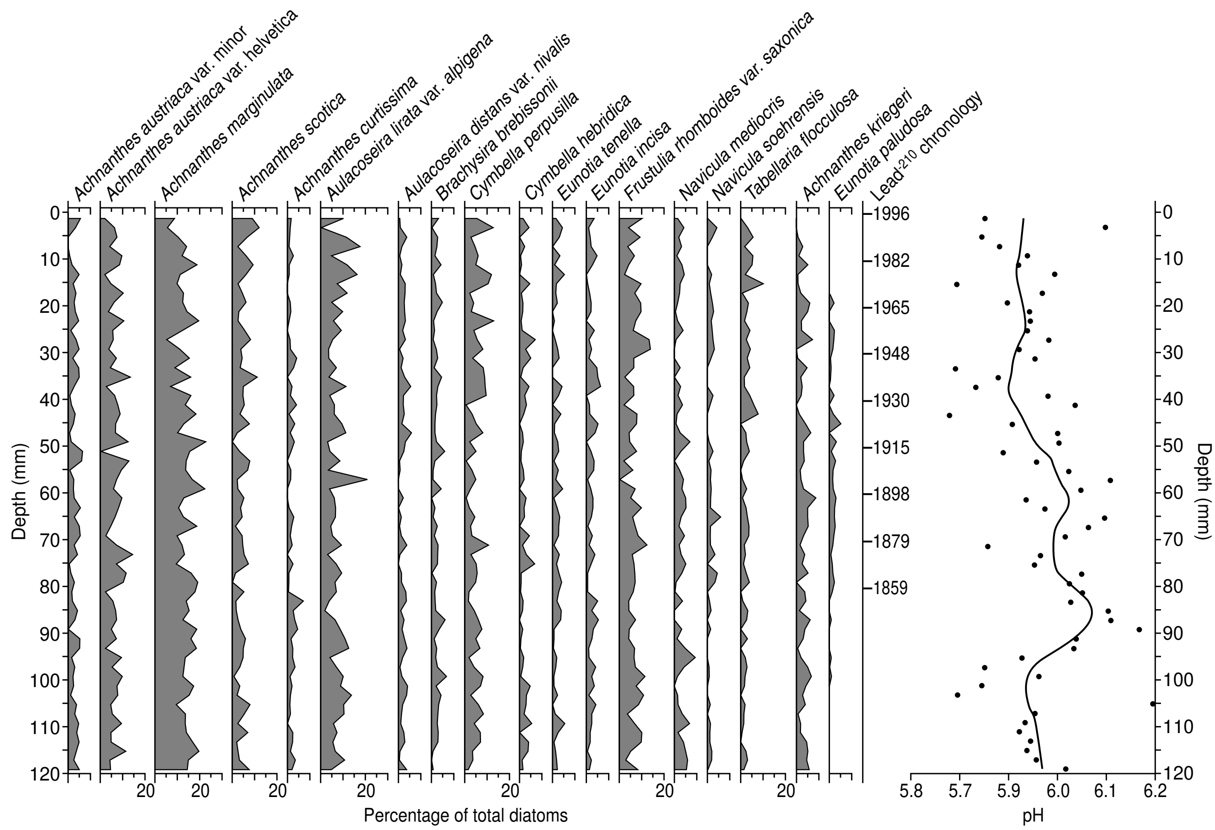

Figure 4. Summary diatom percentage diagram (species occurring at abundances of greater than 5% in at least one sample) with diatom-based pH reconstruction (line is a LOESS smoother) for core ØVNE4.

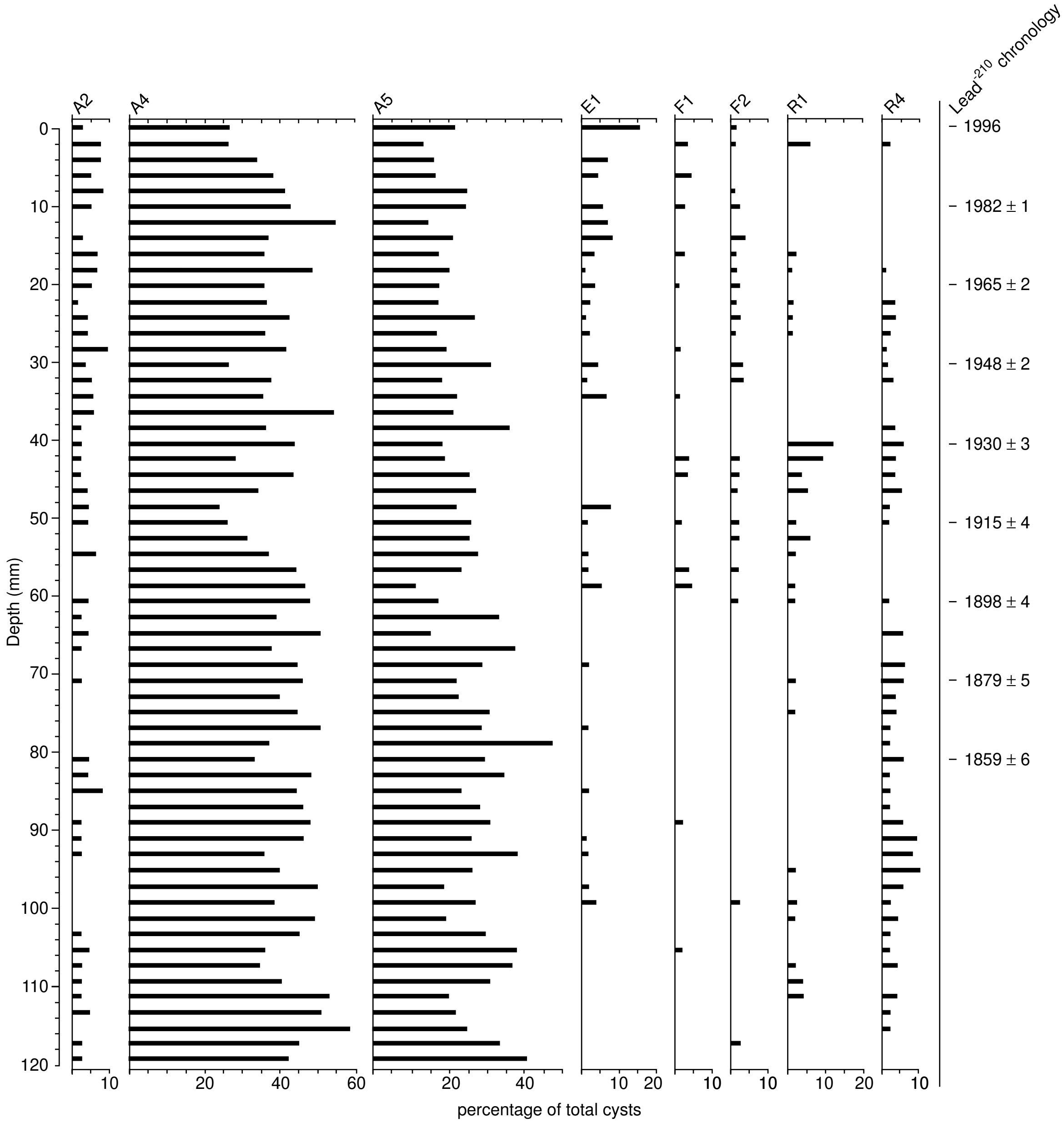

Figure 5. Percentages of selected chrysophyte stomatocyst types for core ØVNE4.

increases from less than 5% at 100 mm to a maximum of over 15% at the surface. Small cysts with ridge-like ornamentation (F1 and F2) also appear more common in the upper part of the sequence, along with smooth, collared cysts > 5 μm (A2). Cyst types R1 and R4 of different sizes, with diffuse spines, with and without a collar show maxima in the middle part of the profile. However, given the absence of ecological data for these cysts it is not useful to speculate upon the reasons for these small changes.

Cladoceran analysis

A total of 15 cladoceran taxa were identified, a relatively high number when compared with the sediment assemblages in many mountain lakes. Littoral chydorids were the most numerous species, whilst *Bosmina longispina* was the only true planktonic species found and also the most abundant taxon in the samples, representing between 30 and 70% of the total.

No clear changes in the species composition are de-

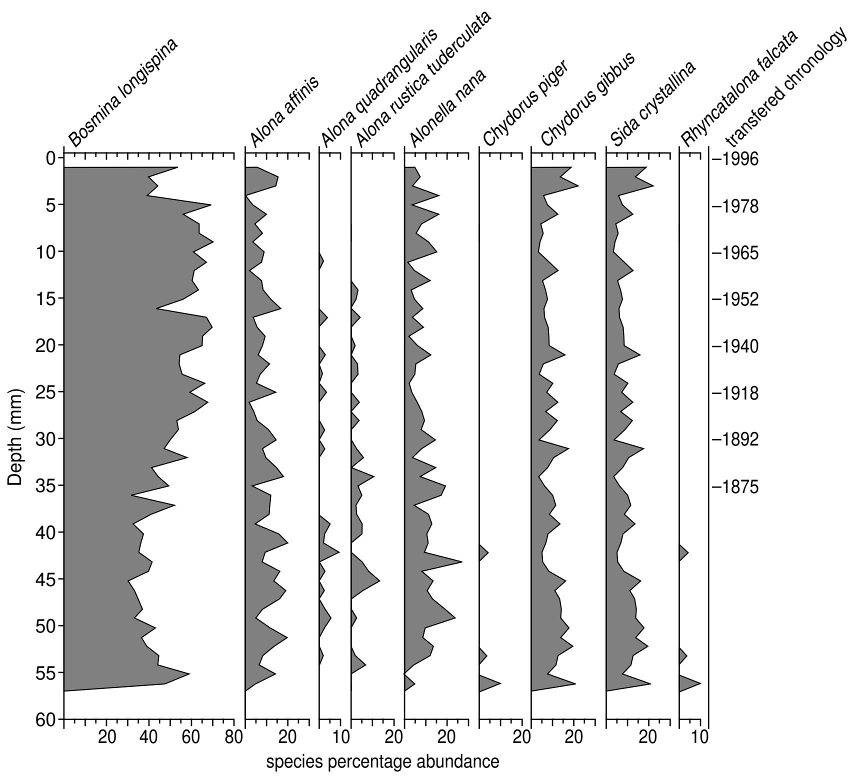

Figure 6. Percentage cladoceran analysis, core ØVNE5.

tectable in Øvre Neådalsvatn during the last 200 years (Figure 7). The proportions of most species, such as *Alona affinis*, *Alonella nana*, *Chydorus gibbus* and *Sida crystallina*, have remained constant through time. The percentage occurrence of *Bosmina longispina*, the most abundant species, increased from the 1960's to the early 20th century. After this time the species proportion in the Cladocera community remained fairly constant until the 1970's. During recent decades it has decreased from 70 to 40–50%.

The total number of cladoceran species in Øvre Neådalsvatn has decreased slightly during the last 200 years. *Chydorus piger* and *Rhyncatalona falcata* disappeared at the turn of the 20th century, whereas *Alona quadrangularis*, *Alona rustica tuberculata* and *Alona excisa* were found in samples up to the 1960's.

Chironomid analysis

A total of 31 samples were analysed from the uppermost 13.2 cm of core ØVNE6, going back to about 1790 AD (Figure 8). Each 0.2 cm sample was analysed separately. After inspection of the results, the samples were amalgamated to 1 cm intervals. More than 1500 head capsules were recovered and identified, comprising a minimum of 51 chironomid taxa. Of these taxa, 35 can be referred to as truly lentic, while 16 are regarded as lotic or even terrestrial. In recent samples taken from the lake, including the inlet and outlet rivers, 69 taxa have so far been recorded. About 35 taxa were common to both investigations.

The dominant species in all samples was *Heterotrissocladius brundini*, with an average of 42% of all head capsules found throughout the core. Next followed *Micropsectra radialis* and *Micropsectra* cf. *insignilobus*, each with an average of almost 9%. These three species on average make up around 60% of each sample. The distribution of *H. brundini* shows little fluctuation between samples. There was a slow decrease of *Micropsectra* cf. *insignilobus* up-core, and at the same time a slow increase in *Micropsectra radialis*. The lotic taxa, *Diamesa* spp., *Eukiefferiella claripennis* and *E.* cf. *corulescens* together form an important part of the fauna in the deepest of the analysed samples, from around 1800 AD. The other species of the subfossil chironomid community were represented in small numbers only, and showed minor fluctuations.

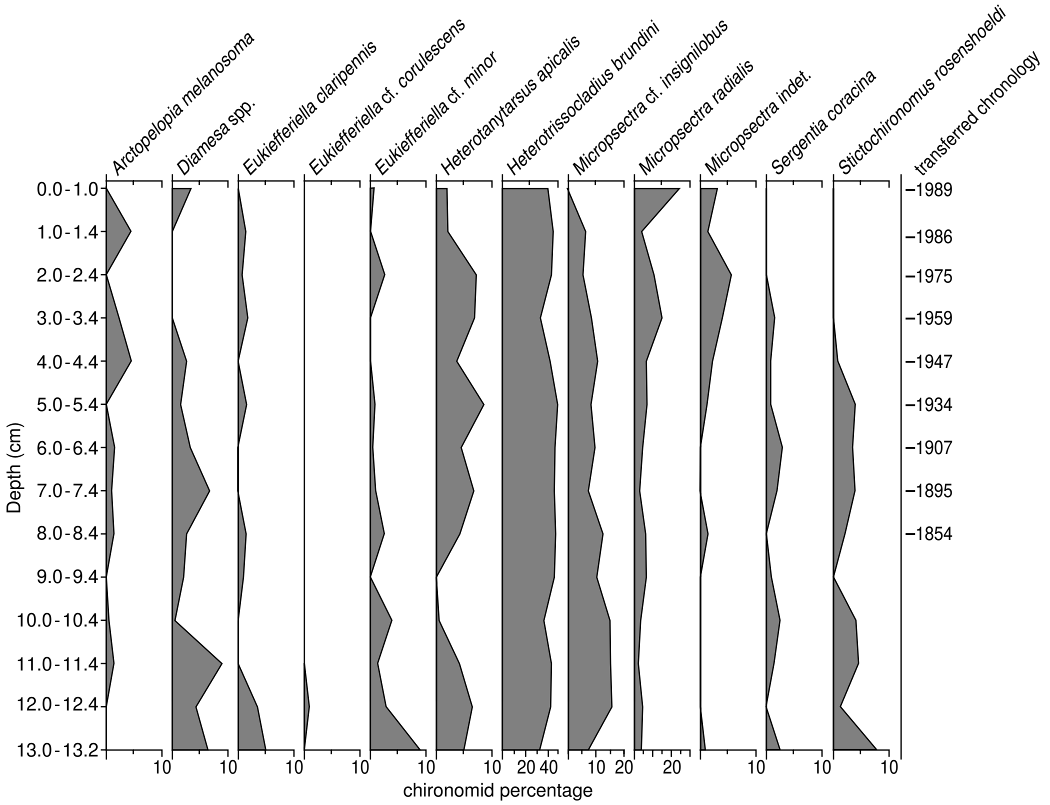

Figure 7. Percentage chironomid analysis, core ØVNE6.

Discussion

The historical record of atmospheric pollution

Both mineral magnetics and SCPs provide a record of atmospheric pollution. The presence of magnetosomes in the uppermost 5 cm of core ØVNE7 confirms that atmospheric deposition has increased at the lake. The magnetic record of atmospheric deposition is supported by the short SCP record of core ØVNE4.

Low SCP concentrations throughout suggest that there have been low levels of acid deposition since the 1950's, with peak SCP concentrations in 1980. Whilst these levels are similar to those of other Norwegian sites, the timing of the maximum concentration in the ØVNE4 core is about 10 years later. However, the temporal trends appear to reflect those of Norwegian oil combustion.

Diatom and chrysophyte cyst analysis

No significant changes in the taxonomic composition of diatoms or chrysophyte cysts were apparent in core ØVNE4. The dominant taxa in each case remained stable from the late 18th century until the present. This was also reflected in the diatom-based pH reconstruction, which showed no consistent trends over the period of study. It is therefore concluded that neither the low level of acid deposition nor the effect of recent climate change have had detectable impacts on the dominant species composition of these algae. However, there is some evidence for changing species composition of less abundant diatom species, but the cause of this is not known.

In order to consider the changes in the entire chrysophyte cyst assemblages, the variation in cyst composition was reduced to four principal components and these were regressed against reconstructed climate variables. However, these chrysophyte cyst data show no significant correlation with instrumental climate data.

Chironomid analysis

The chironomid species found in the ØVNE6 core are typical of oligotrophic mountain freshwater habitats and are commonly found all over southern Norway. The chironomid species composition in the sediment record indicates that Øvre Neådalsvatn has been a relatively stable habitat during approximately the last 200 years. The numerically most important species, *H. brundini*, displays a stable distribution up-core. This is in contrast with the results from a similar analysis performed in Vassdalsvatn (Schnell, 1996), a lake situated only 10 km north of Øvre Neådalsvatn and at the same altitude. In Vassdalsvatn *H. brundini* showed a striking development during the last 200 years, with a relative abundance that increased steadily from about 35% to more than 80% of the chironomid fauna in the top samples. Because the lakes are so close to each other, microclimatic conditions may be of importance in explaining this difference. Øvre Neådalsvatn is situated in a valley opening to the south-west, and is more exposed to solar influx than Vassdalsvatn, which is situated in a deep, narrow valley open to the north but otherwise surrounded by high mountains. The development of *H. brundini* in Vassdalsvatn was interpreted as an indication of colder water temperatures (Schnell, 1996). Other strong climate indicator species, such as *Heterotrissocladius subpilosus* and *Pseudodiamesa arctica*, were found only sporadically in the sediments from Øvre Neådalsvatn.

The trends found in the distribution of the two *Micropsectra* species are difficult to interpret, since both are cold-adapted, oligotrophic deep-water species. According to Sæther (1979), they have identical ecological requirements. No consistent pattern was found in the distribution of the other lentic taxa.

Large numbers of non-lacustrine taxa are found throughout the whole core. Most of these are typical lotic species normally found in high altitude localities in this region, while a few usually live in terrestrial habitats. However, taxa from both these categories can often be found in the littoral zone of high mountain lakes (Aagaard, 1978). Some of these taxa may have been washed in by the inlet river during periods of heavy precipitation. In terms of the number of taxa, the non-lacustrine category is important, but when considered as a percentage of the total chironomid fauna their contribution is much less significant. Based on both the subfossil and contemporary chironomid fauna (Wathne et al., 1995, 1997), there are no indications of any impact of acidification on Øvre Neådalsvatn.

Cladoceran analysis

The most abundant Cladocera species in the data set were *Bosmina longispina*, *Alona affinis*, *Alonella nana*, *Chydorus gibbus* and *Sida crystallina*. The first three species, together with several other species in the Øvre Neådalsvatn core, such as *Acroperus harpae* and *Eurycercus lamellatus*, can be classified as arctic and subarctic according to their latitudinal affinities (Harmsworth, 1968; Rautio, 1998; Korhola, 1999). They also occur regularly in the earliest postglacial assemblages in lakes in Europe (Goulden, 1964; Whiteside, 1970; Hofmann, 1978; Korhola, 1992). In addition, *Bosmina longispina* is typically associated with oligotrophic conditions (Flossner, 1972) and rather harsh climatic conditions (Hofmann, 1978), but has also been found recently in acidic lakes and wetlands in southern Fennoscandia (Nilssen & Sandøy, 1990; Korhola, 1992).

The large number of littoral species in the data set suggests that the lake has a high habitat diversity. For example, one of the most frequent species, *Sida crystallina*, is strongly associated with littoral macrophytes. However, the high ratio of littoral to pelagic species in the sediment core may not represent the true situation in the lake. Of the pelagic species, only Bosminidae and Daphniidae leave recognisable remains in the sediment, whereas most littoral species are well preserved (Frey, 1960; Whiteside, 1970; Hofman, 1987; Hann, 1989).

Rhyncatalona falcata and *Chydorus piger* were not found in the sediment after 1900 and are usually reported as indifferent and relatively rare species (e.g., Sandøy & Nilssen, 1986). Of the three species that disappeared in the 1960's, *Alonella excisa* is considered an acidobiontic bottom-dweller, with a usual preference for pH < 5.5 (Krause-Dellin & Steinberg, 1986). *Alona rustica* has been similarly reported in acidic lakes (Sandøy & Nilssen, 1986), whereas the form *tuberculata*, which refers to the rough surface of the carapace, is usually considered to result from unfavourable conditions affecting the nominate species. *Alona quadrangularis* is a benthic species occurring mainly in the littoral area. The littoral status of all the species disappearing from the sediments of Øvre Neådalsvatn suggests that if there is any common explanation for their disappearance, the mechanism most strongly affects the littoral region. However, based on the composition of the most common species and their relatively constant occurrences through time, Øvre Neådalsvatn can be characterised as a stable, cold and oligotrophic lake with a well-formed littoral macrophyte zone. This is consistent with the current state of the lake, although the macrophytes are dominated by bryophytes.

Regression analysis of core and reconstructed instrumental climate variables

In total, as for the other MOLAR sites, six temperature variables were compared with sediment core data. These were: mean summer temperature 1 (June, July and August: JJA); mean summer temperature 2 (July, August and September: JAS); mean winter temperature (December, January and February: Wint); a continentality index, the difference between JJA and Wint (Cont); mean annual temperature, the mean of all twelve months (Ann); and mean autumn temperature (September, October and November: Aut).

For all reconstructed instrumental climate parameters, the longest span length (span = 0.5) gives the lowest p-values and the greatest number of statistically significant correlations at the 0.1 and 0.01 levels. However, the p-values must be interpreted with caution because the sequence of samples is autocorrelated, resulting in an apparent increase in the correlation. For the response variables (sediment core parameters) it is evident that the species composition in one specific sample is not independent of the species composition in earlier samples. Further, this problem is most serious when the greatest amount of smoothing is applied to the predictor variables, i.e., reconstructed instrumental climate. Therefore the appearance of a better correlation in all cases, as a result of applying more time-averaging to instrumental data, may be a statistical artefact.

A second statistical problem is the result of carrying out a large number of regressions of predictors and response variables. If all variables were independent and randomly related to one another, by chance alone one tenth of the p-values would be lower than 0.1 and one hundredth of the p-values would be lower than 0.01.

To illustrate the problem of autocorrelation and to provide a control comparison, depth in each of the cores was regressed against each of the climatic variables. In all cores, for each of the climate variables, none of the core response variables shows a greater number of p-values, significant at the 0.1 and 0.01 levels, than simply comparing with depth in the core. This observation suggests that none of the response variables shows a statistically significant response to climate and any apparently significant correlations are the result of autocorrelation.

Those parameters that do show significant p-values tend to be the simplest parameters measured, for example the lithological measurements of DW and LOI. A further problem that occurs, however, at least in the upper part of the sequence, is that there is a consistent trend in these simple parameters which may be related to other factors such as loss of water by the sediment or atmospheric deposition, rather than any trend in temperature. Given the increasing trend in temperature during this period, sediment artefacts may have resulted in a spurious correlation even of these response variables.

Conclusions

Øvre Neådalsvatn is an oligotrophic, high altitude lake of moderate size, which has suffered relatively little impact from atmospheric deposition compared with similar lakes elsewhere in Europe. The fauna and flora of the lake are typical of an oligotrophic lake subject to a prolonged period of ice cover. No response to acid deposition is apparent from the composition of sediment core fossil assemblages, or from environmental reconstructions based on diatoms, chrysophytes, cladocerans and chironomids. Having confirmed that the level of acid deposition and changes within the catchment area, indicated for example by the sediment lithology and mineral magnetic signals, are of low magnitude, it is appropriate to consider the high resolution record from the Øvre Neådalsvatn cores in terms of climatic response.

Agustí-Panareda and Thompson (this issue) have shown from their reconstructed climate series for Øvre Neådalsvatn that there has been an increasing trend in mean annual temperatures of about 1 °C since 1900. This reconstruction is subject to an error of approximately 0.1–0.3 °C. The warming trend at Øvre Neådalsvatn, in the western part of Scandinavia, is less pronounced than that in the eastern part of the region. As would be anticipated for lakes further from the ameliorating influence of the Atlantic, there is a more pronounced, or detectable response to reconstructed climate warming. Further, at Øvre Neådalsvatn, prior to 1900, in the period from 1781 there have been periods with mean annual temperatures equivalent to the relatively high mean annual temperatures of recent years. It can therefore be argued that over the period studied, despite the high-resolution and multi-proxy nature of the analytical techniques employed, the sediment record appears insensitive to climate change at the time resolution that is of relevance. No biological amplification of a climate signal is apparent.

In addition to the problem of the relatively small magnitude of the climate change involved, time-averaging processes affecting the sediment core may have attenuated any potential response, despite the attempt to use high-resolution sampling techniques. The question of the limits of detection has also been discussed in relation to atmospheric deposition measured by SCPs. Levels of acid deposition in recent decades may, for example, have been high enough to counteract increased pH as a result of increasing mean annual temperatures (Schmidt & Psenner, 1992). Changes in the intensity of non-anthropogenic catchment erosion, not clearly linked to climatic change, but evidenced in the lithological and mineral magnetic records, may also have obscured any climate response.

No significant changes were recorded in whole assemblages of diatoms, chironomids, cladocerans or in pigments. However, changes in diatom assemblages, for example, are detectable only in species which generally occur at less than 1% maximum abundance whilst the dominant diatom flora of the lake remains stable. The diatom-based pH reconstruction for the lake does not change significantly and is insensitive to the changes in the presence or absence of these rare taxa. Similarly the dominant chironomid and cladoceran taxa remain relatively stable during this period. Fluctuations in a number of pigment parameters were detected; however there is no statistically significant correlation with reconstructed instrumental climate at the lake.

The principal difficulty in comparing the sediment record directly with the precise, annual calendar chronology of the instrumental-based climate reconstruction is in obtaining a precise match with the core's radiometric chronology. Given the low magnitude of the temperature fluctuations, even with a possible amplification via a biological response, the uncertainties of matching these two classes of data appear, for this lake, to be problematic.

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References

Aagaard, K., 1978. The Chironomidae of the exposed zone of Øvre Heimdalsvatn. Holarct. Ecol. 1: 261–265.

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. & F. Oldfield, 1978. The calculation of ^{210}Pb dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. Catena 5: 1–8.

Appleby, P. G., N. Richardson & P. J. Nolan, 1992. Self-absorption corrections for well-type germaniun detectors. Nucl. Inst. Meth. B71: 228–233.

Battarbee, R. W., 1986. Diatom analysis In Berglund B. E. (ed.), Handbook of Holocene Palaeoecology and Palaeohydrology. John Wiley, Chichester, 527–570.

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 palaeolimnological and instrumental evidence of climate change for remote mountain lakes over the last 200 years. J. Paleolim. 28: 161–179.

Battarbee, R. W. & M. J. Kneen, 1982. The use of electronically counted microspheres in absolute diatom analysis. Limnol. Oceanogr. 27: 184–188.

Cameron, N. G., N. L. Rose, P. G. Appleby, Ø. A. Schnell, R. W. Battarbee, S. T. Patrick & R. J. Flower, 1993. AL:PE 1: Palaeolimnology. ECRC Research Report No. 4. Environmental Change Research Centre, University College London.

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.

Duff K. E., B. A. Zeeb & J. P. Smol, 1995. Atlas of Chrysophycean Cysts. Kluwer Academic Publishers, Dordrecht, The Netherlands, 189 pp.

Flössner, D., 1972. Kiemen- und Blattfüsser, Branchipoda: Fischläuse Branchiura. Die Tierwelt Deutschlands. 60: 1–499.

Frey, D. G., 1960. The ecological significance of cladoceran remains in the lake sediments. Ecology 41: 684–699.

Glew, J. R., 1989. A new trigger mechanism for sediment samplers. J. Paleolim. 2: 241–243.

Goodwin, T. W. (ed.), 1976. Chemistry and Biochemistry of Plant Pigments. Academic Press.

Goulden, C. E., 1964. The history of the cladoceran fauna of Esthwaite Water (England) and its limnological significance. Arch. Hydrobiol. 60: 1–52.

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.

Hann, B. J., 1989. Cladocera. Methods in Quaternary Ecology. Geosci. Canada. 16.

Harmsworth, R. V., 1968. The developmental history of Blelham Tarn (England) as shown by animal microfossils, with special reference to the Cladocera. Ecol. Monogr. 38: 223–241.

Hofmann, W., 1978. *Bosmina* (Eubosmina) populations of Grosser Plöner See and Schöhsee lakes during late-glacial and postglacial times. Pol. Arch. Hydrobiol. 25: 167–176.

Hofmann, W., 1987. Cladocera in space and time: analysis of lake sediments. Hydrobiologia 145: 315–321.

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

Korhola, A., 1992: The early Holocene hydrocere in a small acid hilltop basin studied using crustacean remains. J. Paleolim. 7: 1–22.

Korhola, A., S. Sorvari, S., M. Rautio, P.G. Appleby, J. A. Dearing, N. L. Rose, A. Lami & N. G. Cameron, 2002. A multi-proxy analysis of climate impacts on recent ontogeny of subarctic Lake Saanajärvi in Finnish Lapland. J. Paleolim. 28: 59–77.

Krause-Dellin, D. & C. Steinberg, 1986. Cladoceran remains as indicators of lake acidification. Hydrobiologia 143: 129–134.

Lami, A., F. Niessen, P. Guilizzoni, J. Masaferro & C. A. Belis, 1994. Palaeolimnological studies of the eutrophication of volcanic Lake Albano (central Italy). J. Paleolim. 10: 181–197.

Lami, A., P. Guilizzoni & A. Marchetto, 2000. High resolution analysis of fossil pigments, carbon, nitrogen and sulphur in the sediments of eight European Alpine lakes: the MOLAR project. In: Lami, A., N. Cameron & A. Korhola (eds), Paleolimnology and Ecosystem Dynamics at Remote European Alpine Lakes. J. Limnol. 59(suppl. 1): 15–28.

Nilssen, J. P. & S. Sandøy, 1990. Recent lake acidification and cladoceran dynamics: surface sediment and core analyses from lakes in Norway, Scotland and Sweden. Phil. Trans. r. Soc., Lond. B 327: 299–309.

Palecki, M. A. & R. G. Barry, 1986. Freeze-up and break-up of lakes as an index of temperature changes during the transition seasons: a case study for Finland. J. Clim. Appl. Meteor. 25: 893–902.

Rautio, M., 1998. Community structure of crustacean zooplankton in subarctic ponds effects of altitude and physical heterogeneity. Ecography 21: 327–335.

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., 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.

Sandøy, S. & J. P. Nilssen, 1986. A geographical survey of littoral crustacea in Norway and their use in paleolimnology. Hydrobiologia 143: 277–276.

Schmidt, R. & R. Psenner, 1992. Climatic changes and anthropogenic impacts as causes for pH fluctuations in remote high alpine lakes. Documenta Ist. Ital. Idrobiol. 32: 31–57.

Schnell, Ø. A., 1996. Chironomids as a tool in monitoring climate change. Part 1: Effects of climate changes on subfossil chironomid communities in alpine lakes. Project report to the Norges Forskningsråd.

Sæther, O. A., 1979. Chironomid communities as water quality indicators. Holarct. Ecol. 2: 65–74.

Thompson, R. & F. Oldfield, 1986. Environmental Magnetism. Allen and Unwin, London, 227 pp.

Walden, J., F. Oldfield & J. P. Smith (eds), 1999. Environmental Magnetism: a practical guide. Technical Guide, No. 6: Quat. Res. Assoc., London, 35–62.

Wathne, B. M., S. T. Patrick, D. Monteith & H. Barth (eds), 1995. AL:PE project part 1. Ecosystems Research Report, 9, Report EUR 16129 EN, European Commission, Luxembourg, 292 pp.

Wathne, B. M., S. Patrick & N. G. Cameron, 1997. AL:PE – acidification of mountain lakes: palaeolimnology and ecology. Part 2 – remote mountain lakes as indicators of air pollution and climate change. NIVA report 3538-97, Oslo.

Whiteside, M. C., 1970. Danish chydorid Cladocera: modern ecology and core studies. Ecol. Monogr. 40: 79–118.

Züllig, H., 1985. Pigmente phototropher Bakterien in Seesedimenten und ihre Bedeuntung für die Seenforschung. Schweiz. Z. Hydrol. 47: 87–126.