Recent environmental change and atmospheric contamination on Svalbard as recorded in lake sediments – synthesis and general conclusions *

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Abstract

The major patterns of biostratigraphical and geochemical change detected in a multidisciplinary study on recent environmental change and atmospheric contamination on Svalbard are summarised and synthesized. The patterns discussed are changes in sediment accumulation rates, organic matter accumulation rates, atmospheric contaminants, and biological assemblages (diatoms, chrysophyte cysts, chironomids). Possible environmental factors that may have influenced these patterns are discussed, in particular the role of atmospheric contamination (including the deposition of nitrogen-compounds), local human impact, and recent climatic change. The major conclusions are (1) sediment accumulation rates show consistent temporal and geographical patterns with rates increasing towards the present-day and highest in the south, (2) sediment organic-matter accumulation rates increase markedly in the last 50 - 100 years, (3) atmospheric contamination is a combination of local and regional sources, (4) sediment inorganic geochemistry suggests catchment and lake responses to climate change in the last 30 - 50 years, (5) all lakes show a marked increase in the rate of biotic compositional changes in the last 50 - 100 years, and (6) Svalbard lakes appear to be highly dynamic and show considerable biotic and sedimentary changes in recent decades. The most likely cause of many of the observed changes is recent climatic change, with some local human activity at one site. Detailed interpretation of the observed changes is problematic given current limited knowledge about high Arctic limnology, biology, and catchment processes.

Figure 1. Map showing the location of the lakes mentioned in the text. The inset map shows the location of Svalbard in relation to Greenland, Iceland, Fennoscandia, the United Kingdom (UK), and the North Pole.

Introduction

This paper attempts to summarise and synthesise the major biostratigraphic, geochemical, and sedimentary patterns detected in the multidisciplinary study on recent environmental change and atmospheric contamination on Svalbard as recorded in lake sediments (Birks et al. 2004a). The patterns discussed are changes in sediment accumulation rates, sediment loss-on-ignition, and organic matter accumulation rates, atmospheric contaminants, and biological assemblages (diatoms, chrysophyte cysts, chironomids). Possible environmental factors that may have influenced the observed patterns are discussed, in particular the role of atmospheric contamination, human impact, and recent climatic changes. The location of the sites discussed here is shown in Figure 1.

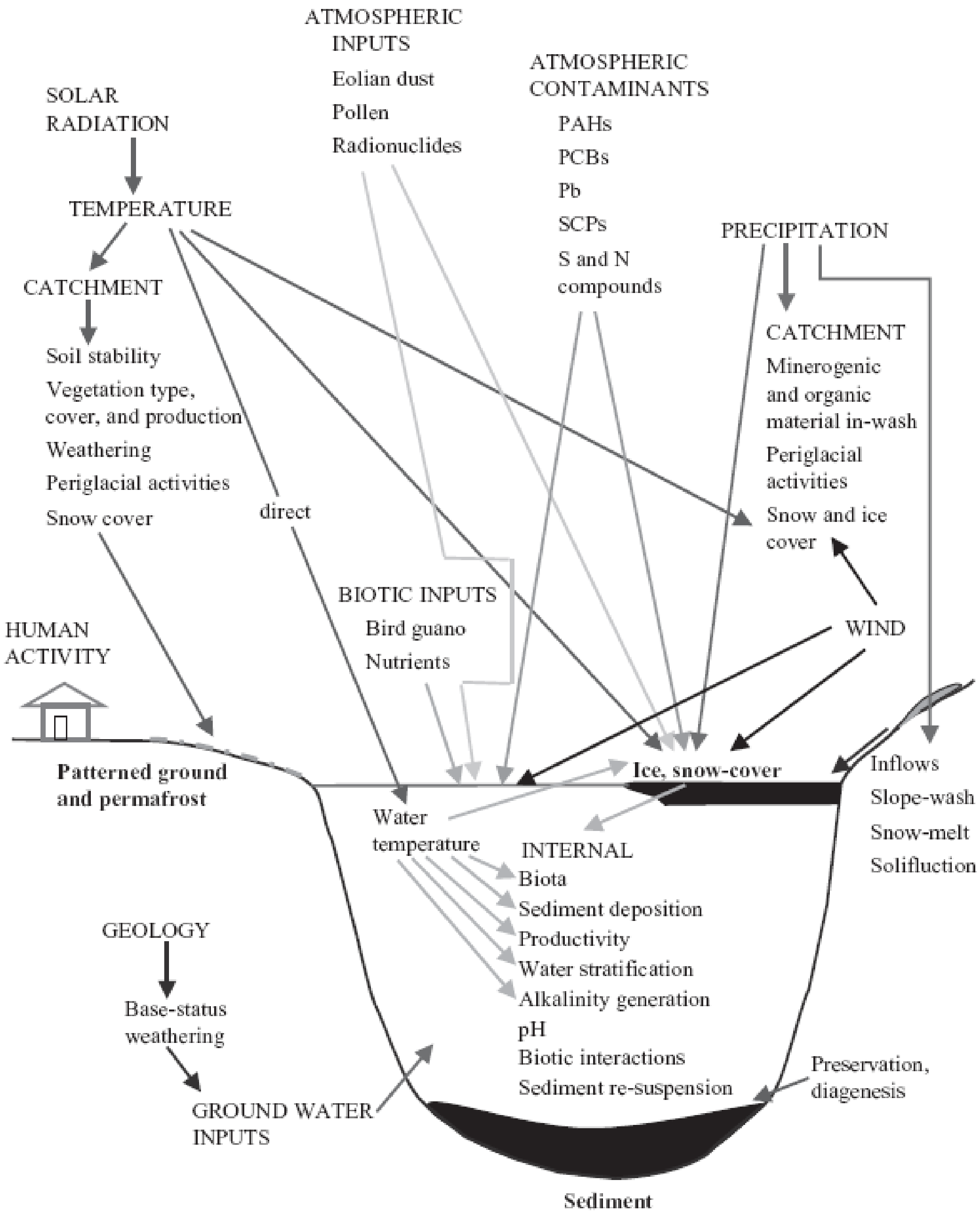

Figure 2. Diagrammatic representation of the major processes occurring in recent centuries that may influence a high Arctic lake ecosystem such as the lakes studied on Svalbard.

As a background to this discussion, a simple diagrammatic representation of the factors that may affect changes in the sediments and lake biota in a high Arctic lake in the recent centuries on Svalbard is presented in Figure 2. The major external driving force is temperature. This has important effects on the lake catchment, for example in influencing soil stability, periglacial activities, the length of the growing season and hence the vegetation type and cover and biomass production, physical and chemical weathering, soil development, and the extent and length of snow cover. In combination with precipitation and wind, temperature determines the amount of snow and ice-cover in the catchment and on the lake. Precipitation also influences the amount of minerogenic and organic material inwash, the type of periglacial activity, and the weathering of nutrients such as silica and phosphorus and of base cations from the catchment (White and Blum 1995). Human activity within the catchment may have some local impacts on the lake and its sedimentary record, as can atmospheric inputs, particularly eolian material and atmospheric contaminants such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), Pb, and nitrogen compounds, and biotic inputs from bird guano. The geological and geomorphological setting of the lake influence the base-status of the lake water and the magnitude of inflows, snow-melt, slope-wash, and other inwashing of catchment material, both minerogenic and organic. The catchment thus strongly affects the conditions in the lake, through input of particulate minerogenic and terrestrial organic matter, base cations, and nutrients. The lake ecosystem is itself affected by temperature directly, through water temperature controlling the composition and abundance of aquatic biota, biological productivity, water stratification, and alkalinity (and hence pH) generation. In addition, water temperature can influence the extent and duration of lake ice and snow cover, which can significantly influence growing conditions and the duration of the growing season. Ecological processes within the lake (e.g. biotic interactions) can also occur, changing the overall lake environment. Conditions within the lake and at the sediment-water interface may influence the preservation of fossils, particularly siliceous algae, and some aspects of the geochemical record preserved in the lake sediments.

Sediment accumulation rates, loss-on-ignition, and organic matter accumulation rates

Eight sediment cores from Svalbard have an absolute chronology based on ^{210}Pb radiometric dating (Appleby 2004). The mean sediment accumulation rates for the last 100 years vary by an order of magnitude, ranging from 0.002 - 0.05 g cm^{-2} y^{-1} (0.02 - 0.10 cm y^{-1}). Accumulation rates are generally low at sites in northern Svalbard (Arresjøen, Birgervatnet, ‘Scurvy Pond’) with the ^{210}Pb/^{226}Ra equilibrium point (corresponding to about 150 years accumulation) at sediment depths of 3 - 5 cm, compared to the southern-most lakes (Vassauga (S), Daltjørna (T), Tenndammen (U)) where the equilibrium point is at 8 - 11 cm depth. This geographical pattern in accumulation rates may result from differences in the duration of the ice-free season, in the underlying bedrock and erodibility of the catchments, or in the magnitude of within-lake production between northern and southern Svalbard. Sedimentation rates are generally uniform or monotonically increasing at five sites (Arresjøen, Birgervatnet, ‘Scurvy Pond’, Ytertjørna (Q), Daltjørna (T)). There is a systematic increase in sediment accumulation rates (g cm^{-2} y^{-1}) at many sites since about 1920 - 1930 and in recent decades. Lakes that do not show any changes in sediment accumulation rates since ca. 1920 are Arresjøen and Ossian Sarsfjellet (C), the largest two lakes studied. At three sites there have been significant variations in accumulation rate, mainly caused by episodes of accelerated sediment accumulation between 1890-1910 (Ossian Sarsfjellet (C), Tenndammen (U)) or in the mid 1970s (Vassauga (S) and Tenndammen (U)). There are several possible causes for these episodic increases and for the systematic increases in accumulation rate. The episodic increases may result from local slumps and inwashing as a result of major meltwater or precipitation events (e.g. Ossian Sarsfjellet 1890 - 1910) or as a result of human activity (e.g. Tenndammen mid-1970s). Boyle et al. (2004) show that there is an enhanced sediment accumulation rate in the mid-1970s at Ytertjørna (Q), Vassauga (S), Daltjørna (T), and Tenndammen (U), which they interpret as resulting from an enhanced supply of Ti-rich clastic material from the catchment. They propose that this widespread phenomenon may have been a response to a regional climatic shift. There was a major short-term increase in spring, summer, and, to a lesser extent, winter precipitation from 1965 to 1975 on Svalbard (Førland et al. 1997; Hanssen-Bauer and Førland 1998) that may have increased catchment erosion and input of clastic material. The systematic increases since about 1920 may also result, in part at least, from recent climatic changes, in particular the 25% increase in annual precipitation since 1912 and the increase in annual temperature from 1912 to the late 1930s (mainly an increase in winter temperature) and from the 1960s to the present (mainly a change in spring temperature) (Førland et al. 1997; Hanssen-Bauer and Førland 1998). Such temperature changes could have increased the ice-free period and hence productivity of Svalbard lakes as well as favouring the build-up of soil organic matter in the catchments, whereas the trend towards increased precipitation in the last 90 years may have resulted in a greater erosion and inwash of catchment material into the lakes, all of which would have resulted in an increase in sediment accumulation rates.

The % loss-on-ignition (LOI) at 550ºC profiles for the various sediment cores studied on Svalbard (Jones and Birks 2004; Brooks and Birks 2004; Boyle et al. 2004) show few consistent temporal patterns over the last 200 - 500 years when plotted together except for a marked rise in LOI in the top 1-2 cm (20 - 50 years). Boyle et al. (2004) propose that the major temporal trends in sediment elemental composition on Svalbard are primarily driven by two contrasting sediment sources. First, a clastic sedimentary component derived by catchment erosion and inwash (Figure 2) or re-suspension of littoral sediments enriches the sediment in elements associated with rock-forming minerals. Second, a fine particulate or colloidal sedimentary component, probably derived from catchment soil organic matter (Figure 2), enriches the sediment in organic matter, iron, manganese, and heavy metals. The observed % LOI profiles largely reflect the relative balance between these two components, with the organic component being potentially enhanced by within-lake production of organic matter but also influenced by steady-state progressive diagenetic loss of organic material. When organic matter accumulation rates (g m^{-2} y^{-1}) are estimated for six cores (Boyle et al. 2004), they show a marked increase from about 1900 - 1930 to the present day at all sites except Ossian Sarsfjellet (C). Boyle et al. (2004) propose, based on correlations with other components in the sedimentary geochemistry, that these organic matter accumulation rate increases are largely explicable in terms of an increased allochthonous supply of soil organic matter resulting from enhanced top-soil erosion and inwash of oxidation-resistant soil organic matter (Figure 2). The observed increases in organic concentration cannot be fully explained by diagenesis of a constant supply of organic material leading to an exponential decay with age and depth because of the observed correlations between organic concentrations and other geochemical elements in the sediment record as a whole and in the top few centimentres. The increases in organic concentration in the uppermost samples at Ytertjørna (Q), Vassauga (S), and Daltjørna (T) do not show any correlations with Pb concentration values, suggesting that this organic matter may have a different origin from the underlying allochthonous material. An autochthonous algal origin is therefore proposed. The simplest explanation for the consistent long-term increase in organic accumulation rates in the last 100 years is that it is a result of increased erosion and inwashing of soil organic matter due to the increase (25%) in annual precipitation, in particular autumn, spring, and summer precipitation since 1912 (Førland et al. 1997; Hanssen-Bauer and Førland 1998). We return to the possible causes for the increased organic accumulation rates in the uppermost samples when we discuss patterns in the biological proxies.

In contrast to the long-term trends in rates of organic matter accumulation, the rates of Ti accumulation show no consistent long-term trends (Boyle et al. 2004) but instead show short-lived peaks in four of the six cores examined. Boyle et al. (2004) interpret these peaks as reflecting increased input of clastic material from the catchment. As discussed above, these may have been catchment responses to the marked short-term changes in precipitation between 1965 and 1975 (Førland et al. 1997: Hanssen-Bauer and Førland 1998). It is possible that for Svalbard lakes the accumulation rates of the clastic component of the sediment may largely be a response to short-term changes or extreme events (e.g. floods, human activity), whereas the changing organic component accumulation rates may be a response to long-term trends such as the 100 year increase in annual precipitation or recent temperature changes.

Atmospheric contaminants

Geochemical data suggest that, with the possible exception of Tenndammen (U), evidence for atmospheric contamination by heavy metals is open to doubt (Boyle et al. 2004), because of local site factors that were largely controlled by the supply of soil organic matter and of clastic minerals such as biotite and amphibole. Comparison of observed and expected heavy metal profiles (based on Greenland ice-core data) shows that the Svalbard lakes are generally too insensitive to have recorded a long-transported heavy metal pollution signal because of the natural variability of the sediment record and the weakness of the pollution signal. However, surface-sediment PAH and PCB data, together with data from spheroidal carbonaceous particles (SCP) analyses in surface sediments and ^{210}Pb-dated sediment cores suggest that there is a small, but detectable, impact from local combustion sources superimposed on a long-range transported background of atmospheric deposition (Rose et al. 2004).

The evidence presented by Rose et al. (2004) suggests that the impact of the fossil-fuel combustion sources in the Isfjord (Figure 1) area can be observed within a radius of approximately 60 - 80 km affecting an area of ca. 7,000 - 9,500 km^2. However, Lien et al. (1993, 1995) have shown critical load exceedences for freshwaters in sensitive areas across the whole of Svalbard, and hence the impact from atmospherically deposited contaminants as a result of both local and remote sources may be far more widespread, potentially causing some biological change in the impacted systems (see below).

As discussed by Rose et al. (2004), the SCP/^{210}Pb inventory ratio is the best available metric for inter-site comparisons when considering atmospheric contamination data. It incorporates the full post-industrial depositional history and hence compensates for variations in sediment accumulation rate, as well as for catchment inwash. The most contaminated site found within the Svalbard data-set was Tenndammen (U), only 12 km from Longyearbyen (Figure 1), and this was found to have a SCP/^{210}Pb inventory ratio of over 9,000. Vassauga (S), close to Isfjord, had a ratio of 2,400 whilst all other sites have values between 90 and 750 confirming the contamination of Tenndammen and Vassauga over and above that which might be described as ‘typical’ for Svalbard. A similar value to these ‘typical’ Svalbard ratios has also been found in a nunatak lake in west Greenland, 5 km from the edge of the ice sheet, where the SCP/^{210}Pb inventory ratio was 860 (N.L. Rose unpublished data). In contrast, Solovieva et al. (2002) record SCP/^{210}Pb inventory ratios of 2,500 and 17,500 from sites in the Usa basin of the east-European Russian arctic. Other Arctic SCP/^{210}Pb inventory ratio data are not currently available, although surface-sediment SCP concentrations for sites in the Canadian Arctic (Amituk Lake, Cornwallis Island; 75º03’ N, 93º48’ W), Russian Arctic (Schuchie Lake; 68º45’ N, 161º15’ E), and Iceland (Thingvallavatn; 64º30’ N 21º30’ W) all show similar values (340, 325, 550 g DM^{-1}, respectively) to the Svalbard data-set (430-1485 g DM^{-1}) (N.L. Rose unpublished data).

Despite showing elevated levels of pollutants in the sediment record, by comparison with remote European mountain lakes, even Tenndammen has only received moderate contamination over its post-industrial history. Vassauga shows comparable levels with the cleanest remote European mountain sites known, whereas the remainder of the Svalbard lakes show levels an order of magnitude lower. Øvre Neådalsvatn in mid-Norway and Saanajärvi in Finnish Lapland show SCP/^{210}Pb inventory ratios of 1,865 and 1,345 respectively (Rose et al.

1999), whilst equally 'remote' but slightly more contaminated sites such as the Estany Redo (Spanish Pyrenees) and Jorisee (Swiss Alps) show ratios of 7,350 and 7,000 respectively, equivalent to Tenndammen. Other remote European mountain lake sites show much higher levels of contamination. Starolesnienske Pleso and Nizne Terianske (Slovakian Tatras) show SCP/^{210}Pb inventory ratios of 11,700 and 14,050, respectively, Hagelsee (Swiss Alps) has a ratio of 16,500, whilst Lochnagar (Scottish Highlands) is over 40,000 (Rose et al. 1999). Put in this broader context, the elevated levels of atmospheric contamination recorded by the Tenndammen sediments are low.

Biological assemblages

Modern assemblages

The 23 lakes studied on Svalbard were independently assigned into various groups on the basis of similarities in their modern water chemistry (Birks et al. 2004b), modern chrysophyte cysts assemblages (Betts-Piper et al. 2004), modern diatom assemblages (Jones and Birks 2004), modern chironomid assemblages (Brooks and Birks 2004), modern pollen assemblages (Birks et al. 2004b), and modern catchment flora (Birks et al. 2004b). The six classifications are summarised in Table 1. Note that because of poor preservation or low concentrations (cysts, pollen) or incomplete field surveys (flora), not all classifications are based on all 23 lakes. An obvious question is how similar are the various classifications? This can be answered by calculating Hill's index of similarity between classifications based on information statistics (Moss 1985). It has a range from 0 (no similarity) to 1 (perfect similarity).

Table 1. Classification of Svalbard lakes (A-K, M-U, Arresjøen (Arsj), Birgervatnet (Bir), and 'Scurvy Pond' (Scur)) based on lake-water chemistry, modern chrysophyte cyst, diatom, chironomid, and pollen assemblages, and catchment flora. The group numbers refer to groups within each independent classification, and not to presumed groups across classifications. (- = data not available.)

	Lake chemistry	Chrysophyte cysts	Diatoms	Chironomids	Modern flora	Modern pollen
A	1	1	2	4	1	2
B	1	1	2	4	1	2
C	1	-	1	2	-	3
D	2	1	2	4	2	-
E	2	-	2	4	2	-
F	2	-	2	1	2	-
G	2	2	3	3	2	2
H	2	2	3	2	2	2
I	2	2	3	2	2	2
J	2	3	3	3	2	-
K	2	2	3	2	2	-
M	2	2	3	3	2	1
N	2	2	3	1	2	1
O	3	1	2	4	2	-
P	1	-	1	3	-	-
Q	1	1	2	4	1	2
R	1	-	2	4	1	-
S	1	1	2	4	-	2
T	1	-	1	4	-	-
U	3	-	2	4	-	3
Arsj	2	-	3	2	-	-
Bir	2	-	3	1	2	-
Scur	2	-	2	4	2	-

The highest similarities are between the diatom- and cyst-based classifications (1.0) and between the cyst- and chironomid-based classifications (0.84). The similarities between diatoms and chemistry (0.45) and cysts and chemistry (0.53) are not as high as might have been expected. There is a low similarity between the classifications based on chemistry and chironomids (0.24) whereas the classifications based on diatoms and chironomids (0.56) are more similar than the classifications based on chemistry and diatoms. Interestingly, the classifications based on the cyst, diatom, and chironomid assemblages are more similar between themselves (0.56 - 1.0) than they are between the different biological and chemical classifications (0.24 - 0.53). These results suggest that the modern diatom, cyst, and chironomid assemblages reflect a complex of limnological and catchment variables (e.g. lake depth, landscape setting, catchment vegetation cover), and not only lake-water chemistry.

There is, rather surprisingly, a low similarity (0.25) between the classifications based on modern flora and modern pollen assemblages. This comparison is only based on 8 lakes because the flora was not recorded on a semi-quantitative basis for some of the lakes that contained countable pollen assemblages and because many of the surface sediments did not contain countable pollen assemblages.

Fossil diatom and chironomid assemblages

Numerical analyses were done in an attempt to answer the following questions: (1) what is the magnitude of compositional change in the cores studied stratigraphically for diatoms and chironomids? Do some sites show greater compositional change than others? (2) What is the rate of biotic change at the different sites? Has the rate of change varied over the last 1,000 years?

The first question was addressed by means of detrended correspondence analysis (DCA) and its canonical or constrained equivalent, detrended canonical correspondence analysis (DCCA). DCA and DCCA were selected because, unlike other indirect and direct gradient analytical techniques, sample scores in DCA and DCCA can be expressed in units of compositional change, turnover, or gradient length as 'standard deviation' (SD) units (Hill and Gauch 1980). The distance between samples in DCA or DCCA (if scaled appropriately) provides a measure of the amount of compositional change between samples and within a stratigraphical sequence, as well as a guide to the amount of compositional difference between sequences. DCA has good mathematical properties as shown by studies using simulated data of known properties (ter Braak 1985) and works well in practice with real-life data, as shown in an elegant modern ecological study in Denmark (Ejrnæs 2000).

All the 23 modern diatom samples, the 87 fossil samples from Arresjøen, Birgervatnet, 'Scurvy Pond', and Ytertjørna (Q) (Jones and Birks 2004), and the 251 diatom taxa were ordinated together by DCA (Figure 3a). The environmental (chemical and catchment) variables were regressed onto the DCA axes to help put the DCA ordination results into a modern environmental context (Figures 3b and 3c). The total gradient lengths (SD) of the first DCA axis for each of the four stratigraphical sequences were estimated in a series of separate DCAs and compared with the gradient lengths estimated by DCCA with sample age (Appleby 2004) used as the sole constraining variable. As the stratigraphical sequences cover different time periods, the amounts of compositional turnover and total inertia ('variance') for each sequence were standardised for each site and expressed as SD per 50 years (Table 2).

The same analyses were made using the 23 modern chironomid samples, 59 fossil samples from sites Ossian Sarsfjellet (C), Ytertjørna (Q), and Tenndammen (U), and 24 chironomid taxa (Figures 4a, 4b, and 4c and Table 3).

All DCA and DCCA involved square-root transformed percentage data, detrending by segments, non-linear rescaling, and downweighting of rare taxa, and were implemented using the console version of CANOCO 4.0 (ter Braak and Šmilauer 1998).

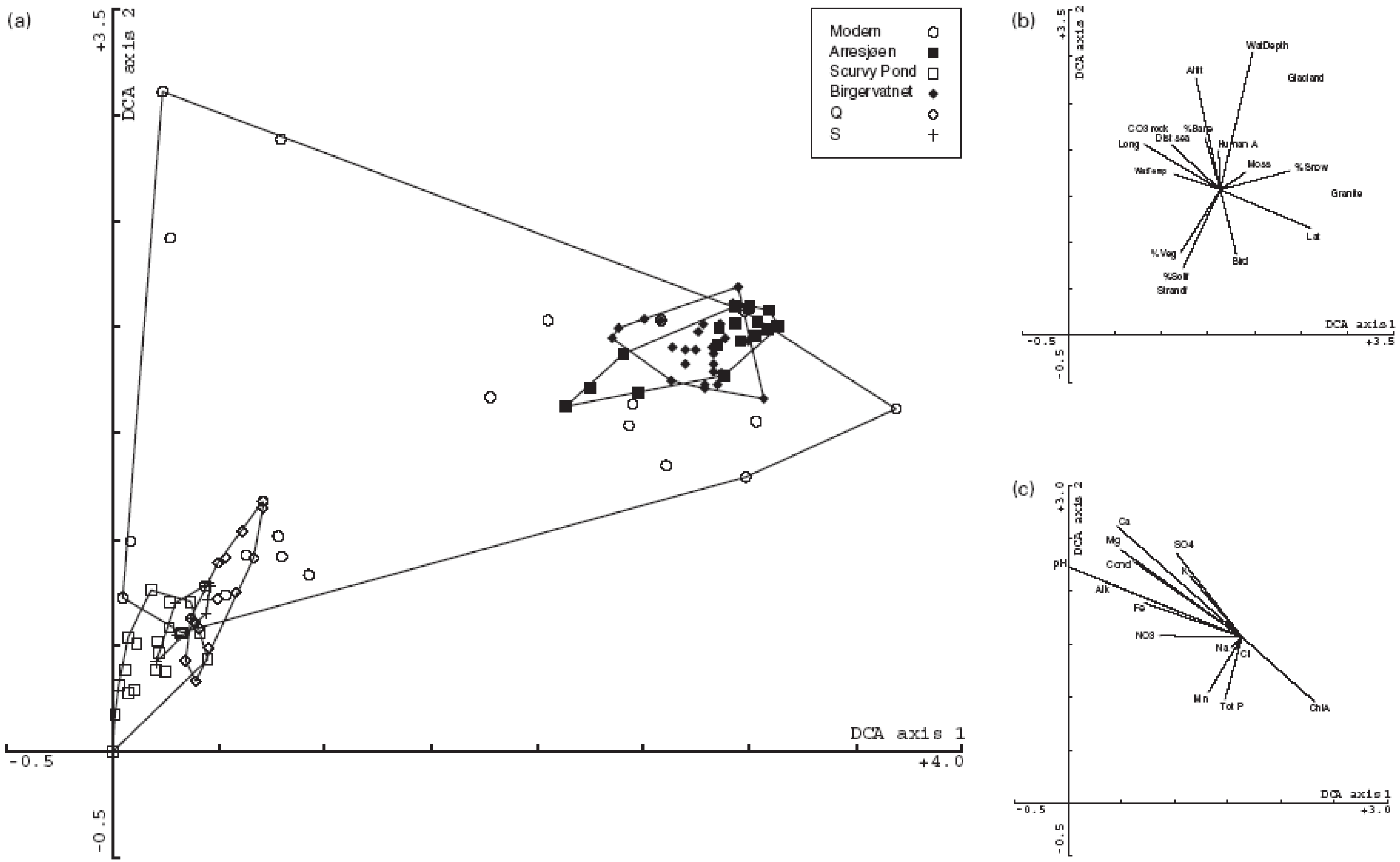

Figure 3. (a) Detrended correspondence analysis (DCA) of all modern and fossil diatom samples. DCA axes 1 and 2 are shown. The axes are scaled in standard deviation units. The axes account for 14.7% and 8.9% of the total inertia (3.96), respectively. The environmental variables (b) and chemical variables (c) for the modern samples are regressed onto DCA axes 1 and 2 and are shown in a biplot representation. Fossil diatom samples for the five lakes are enclosed by convex hulls.

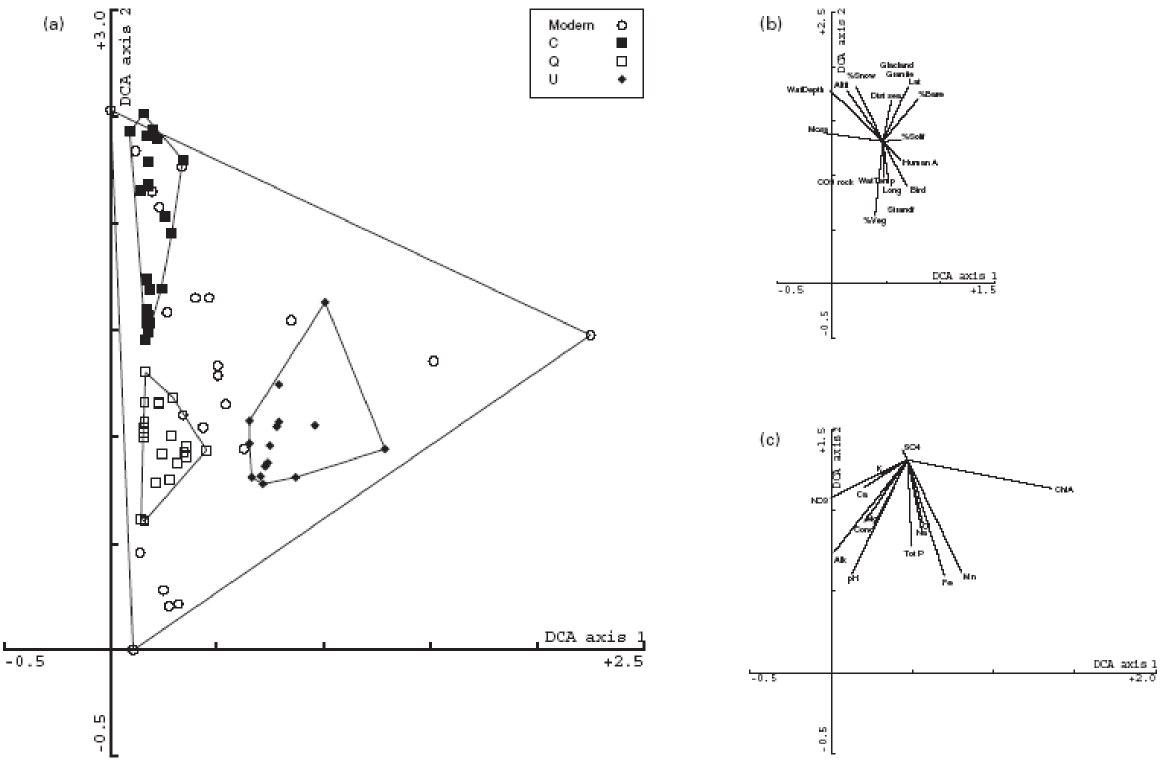

Figure 4. (*a*) Detrended correspondence analysis (DCA) of all modern and fossil chironomid samples. DCA axes 1 and 2 are shown. The axes are scaled in standard deviation units. The axes account for 26.2% and 20.7% for the total inertia (1.68), respectively. The environmental variables (*b*) and chemical variables (*c*) for the modern samples are regressed onto DCA axes 1 and 2 and are shown in a biplot representation. Fossil chironomid samples for the three lakes are enclosed by convex hulls.

Table 2. Summary of DCA and DCCA results of the stratigraphical diatom data from five sites on Svalbard. The inertia, DCA axis 1 length, and DCCA axis 1 length are standardised to 50 years and multiplied by 100. SD = standard deviation units.

Site	Approx. duration (y)	Total inertia	DCA axis 1 (SD)	DCCA axis 1 (SD)	Inertia 50 y^{-1} (x100)	DCA turnover 50 y^{-1} (x100)	DCCA turnover 50 y^{-1} (x100)
Arresjøen	1400	0.938	1.696	1.670	3.350	6.057	5.964
Birgervatnet	1010	1.520	2.007	1.187	7.524	9.936	5.876
'Scurvy Pond'	970	0.470	0.870	0.811	2.423	4.484	4.180
Ytertjørna (Q)	700	0.682	1.290	0.880	4.871	9.214	6.285
Vassauga (S)	180	0.829	1.599	1.208	23.03	44.412	33.556

Table 3. Summary of DCA and DCCA results of the stratigraphical chironomid data from three sites on Svalbard. The inertia, DCA axis 1 length, and DCCA axis 1 length are standardised to 50 years and multiplied by 100. SD = standard deviation units.

Site	Approx. duration (y)	Total inertia	DCA axis 1 (SD)	DCCA axis 1 (SD)	Inertia 50 y^{-1} (x100)	DCA turnover 50 y^{-1} (x100)	DCCA turnover 50 y^{-1} (x100)
Ossian Sarsfjellet (C)	640	0.498	1.470	1.172	3.891	11.484	9.156
Ytertjørna (Q)	510	0.498	1.323	0.919	4.882	12.971	9.010
Tenndammen (U)	730	0.894	3.448	0.616	6.123	23.616	4.219

The second question was addressed by rate-of-change analysis (Grimm and Jacobson 1992; Lotter et al. 1992; Zeeb et al. 1994; Birks et al. 2000). It attempts to quantify the total amount of biostratigraphical change per unit time and has been shown to be a very sensitive measure of biotic change in lake systems, for example in reflecting diatom and chrysophyte responses to experimental eutrophication at Lake 227 in the Experimental Lakes Area of north-western Ontario (Zeeb et al. 1994). The results of rate-of-change analysis are dependent on several factors, including the reliability of the dating chronology and estimates of the sample ages, the measure of compositional difference or dissimilarity measure used, the type of smoothing (if any) used, the time intervals between samples, the sampling density, and the interpolation procedures adopted (Bennett and Humphry 1995; Laird et al. 1998). In this study we have used simple linear interpolation to produce time series at equally spaced time intervals (50 years). No smoothing was used before or after the interpolation. Chord distance (Prentice 1980) was used as the dissimilarity coefficient because it has several attractive mathematical properties when applied to percentage data. Rates of change were estimated as chord distances per 50 years. In an attempt to identify rates of change that are greater than one would expect by chance, given the critical sampling density and inherent variance of each data-set, approximate significance values were obtained by a restricted Monte Carlo permutation test based, in part, on the time-duration or elapsed time test of Kitchell et al. (1987) and, in part, on the restricted Monte Carlo permutation test used in CANOCO 4.0 for time series (ter Braak and Šmilauer 1998). The approximate 95% significance levels for each time series are shown in Figure 5. Any rate-of-change value greater than these levels is unlikely to have arisen by chance sample-to-sample variation, inherent counting errors, sampling density, or sedimentary phenomena.

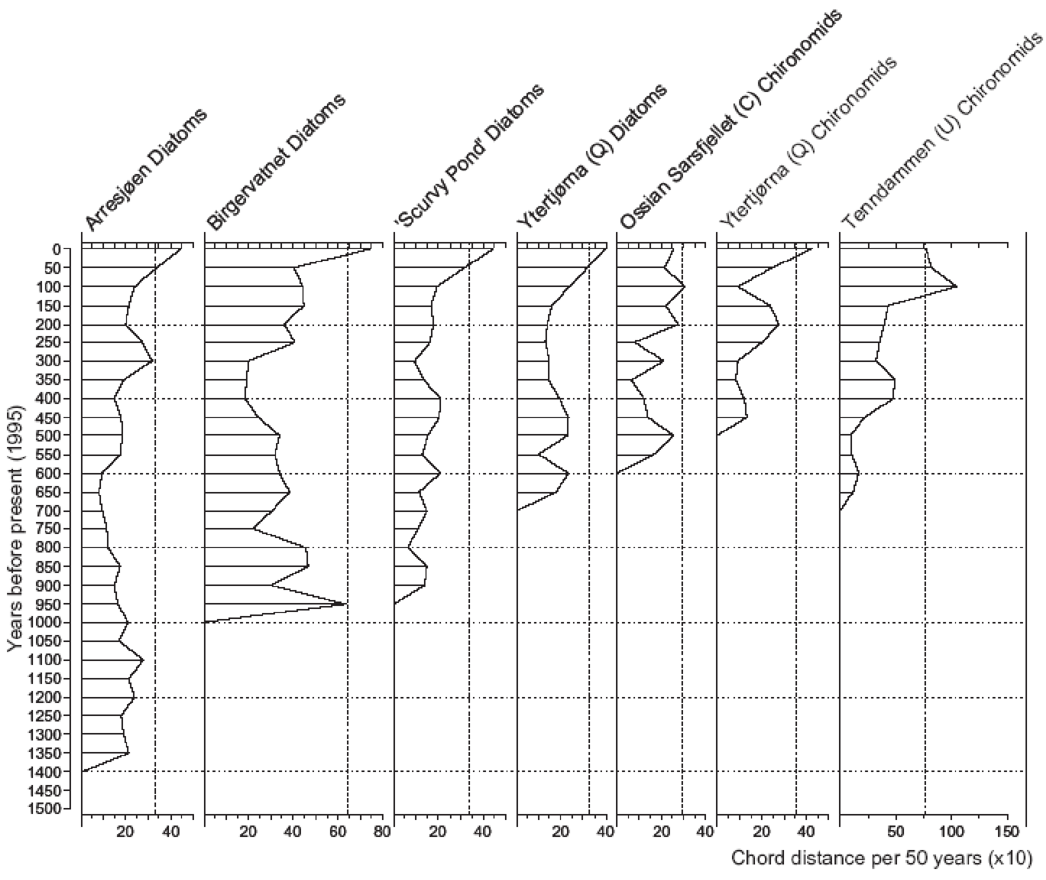

Figure 5. Rates of change for diatoms at four sites and for chironomids at three sites plotted against sediment age before present (1995). The approximate 95% significance levels for the rate-of-change estimates based on restricted permutation tests are shown by the vertical lines. Rates of change lying beyond these significance levels are unlikely to have arisen by chance given the inherent variability and sampling density of the groups concerned. The horizontal lines indicate 200 year intervals and are drawn to help comparison between curves.

The various options selected in the rate-of-change analyses here (interpolation increment, dissimilarity coefficient, no smoothing) are inevitably a compromise and are not 'optimal' for any one time-series given its sampling intensity and chronology. The options used were selected after preliminary analyses and were applied uniformly to all seven time-series in Figure 5 in an attempt to provide a basis for comparing the timings and the extent of rate of change in the different data sets and at the different sites. All computations were done with the program RATEPOL version 1.8 developed by J.M. Line and H.J.B. Birks.

Results

Diatom stratigraphy. The time-standardised total inertia and compositional turnover (as estimated by DCA or DCCA) for the five diatom stratigraphical records (Table 2) are highest at Vassauga (S). These high values are probably an artefact of diatom preservation, with no diatoms being preserved below ca. 1810 AD. When Vassauga is excluded, the highest time-standardised inertia and DCA-based turnover is at the glacially fed Birgervatnet, not surprisingly given the complex and variable diatom stratigraphy at this site (Jones and Birks 2004), possibly reflecting a period of intense erosion near the base of the core with a dominance of the aerophilic *Orthoseira dendroteres*. When compositional turnover in relation to time is estimated by DCCA using sample age as a constraining variable, standardised turnover is relatively similar between sites with values of 0.04 - 0.06 standard deviation (SD) units per 50 y. Surprisingly, the lowest turnover ('Scurvy Pond') and the highest turnover (Ytertjørna) are found at the two shallow strandflat lakes with *Fragilaria*-dominated diatom assemblages (Jones and Birks 2004). Both Arresjøen and Birgervatnet, on acidic bedrock in northwest Svalbard (Figure 1), have turnovers of 0.06 SD per 50 y. They are both deep lakes with diatom assemblages dominated by *Navicula, Aulacoseria,* and *Cyclotella* (Jones and Birks 2004). The generally similar turnovers are shown graphically in the combined DCA of all the modern and fossil diatom samples from Svalbard (Figure 3a). Regression of the chemical and environmental variables for the 23 lakes onto DCA axes 1 and 2 (Figures 3b and 3c) highlight the contrast between the diatom assemblages and stratigraphies at the two deep lakes in glacial landscapes on granite bedrock (Arresjøen, Birgervatnet) and at the three strandflat lakes (Ytertjørna (Q), 'Scurvy Pond', and Vassauga (S)). The stratigraphical changes in the strandflat lakes are interpreted by Jones and Birks (2004) as possibly reflecting increasing nutrients and/or redox changes and increasing anoxia, and both the values of total dissolved P and Mn increase on DCA axes 1 and 2 towards the strandflat lakes (figure 3c). The diatom stratigraphies at Arresjøen and Birgervatnet (Jones and Birks 2004) are interpreted as reflecting either regional climatic changes or specific catchment changes. On the DCA plots (Figures 3a, 3b, and 3c) there are no striking relationships with modern lake chemical or catchment variables. Rate-of-change analysis for the four diatom stratigraphies (there are too few samples at Vassauga for a reliable rate-of-change analysis) shows, when the approximate 95% significance levels are considered, that the only statistical significant rates of compositional change have occurred in the last 50 years at all four sites (Figure 5), except for a statistically significant change at Birgervatnet about 950 – 1,000 years ago.

Chironomid stratigraphy. The time-standardised total inertia and compositional turnover as estimated by DCA (Table 3) are highest at Tenndammen (U) but the compositional turnover as estimated by DCCA (constrained by sample age) at Tenndammen is the lowest of the three chironomid profiles. The reasons for these markedly different estimates for time-standardised compositional turnover using DCA and DCCA are unclear but one possibility is that the samples are very unequally distributed in time because head capsule concentrations are very low in parts of the core and as a result there are no samples between 1890 and about 1540 AD (Brooks and Birks 2004). The estimates of time-standardised inertia and compositional turnover for the Ossian Sarsfjellet (C) and Ytertjørna (Q) chironomid stratigraphies are very similar irrespective of numerical method used (Table 3). The combined DCA plot (Figure 4a) illustrates the generally similar amounts of compositional turnover at these two sites, the greater compositional change at Tenndammen (U), and the relatively small amount of within-site variation compared with the variation represented by the 23 modern chironomid assemblages. Regression of the chemical and catchment variables onto DCA axes 1 and 2 (Figures 4b and 4c) highlights the contrast on DCA axis 2 between the chironomid stratigraphies from the deep oligotrophic Ossian Sarsfjellet (C) and the shallow, high pH Ytertjørna (Q) and the contrast between Ytertjørna (Q) and Tenndammen (U) along the first DCA axis that is correlated primarily with the gradient in chlorophyll *a* values, human activity, and bird presence today (Figures 4b and 4c). Rate-of-change analysis for the three chironomid stratigraphies (Figure 5) show that when the approximate 95% confidence intervals are considered, the only statistical significant rates of compositional change occur in the last 100 years at all three sites, with the exception of Ossian Sarsfjellet where there is a weakly significant rate change 200 - 250 years ago. As Brooks and Birks (2004) discuss, interpretation of the chironomid stratigraphies at these three sites is not straightforward, possibly reflecting subtle changes in lake productivity and pH as a response to climate change (Ossian Sarsfjellet, Ytertjørna) or human impact (Tenndammen).

Chrysophyte cyst assemblages. Because of the absence of countable chrysophyte cyst assemblages in some of the surface sediments and the bottom sediments, changes in cyst assemblages could only be determined for 10 lakes (Betts-Piper et al. 2004). The modern assemblages appear to reflect gradients in lake-water pH and sodium values and lake altitude. Differences between the top and the bottom cyst assemblages are very marked. It appears that lakes that are presently relatively acidic may have become more acidic since the times of the bottom sample (lakes G, H, I, J, K, M, and N), whereas lakes on carbonate-rich bedrock that currently have a high pH have increased their pH in recent times (lakes A and B). The top and bottom cyst assemblages at lake O show little difference in composition (Betts-Piper et al. 2004).

Possible environmental factors

There are several possible factors or ‘forcing functions’ that may have influenced the recent biostratigraphical and geochemical changes recorded in lakes on Svalbard (Figure 2). These include (1) regional and local sources of atmospheric deposition of nutrients from anthropogenic sources (Wolfe et al. 2001; Smol 2002; Saros et al. 2003); (2) climatic changes associated with the ‘Little Ice Age’ (Jones and Birks 2004; Brooks and Birks 2004) and the subsequent recent long-term changes in temperature and precipitation in the 20th century (Førland et al. 1997; Hanssen-Bauer and Førland 1998) and the short-term intervals of elevated precipitation between 1965 and 1975 (Førland et al. 1997: Hanssen-Bauer and Førland 1998); (3) human impact and subsequent abandonment in some lake catchments (e.g. buildings, water extraction, drainage) (Rose et al. 2004; Brooks and Birks 2004); and (4) individual lake and catchment responses to climate change, atmospheric pollution, and human impact resulting from a range of interacting factors such as bedrock geology, catchment topography and size, terrestrial biota, lake chemistry, depth, area, biota, and geographical location (Figure 2). Climate change can directly influence Svalbard lakes by inducing changes in the length of the ice-free season and hence lake production and metabolism and other within-lake processes such as dissolved inorganic carbon speciation (Figure 2; Wolfe 2002) and indirectly by influencing catchment production, biota, weathering, erosion, and subsequent inwashing and eolian dust flux (Figure 2). The relative impact of such factors on a specific lake could be influenced by the range of catchment and limnological parameters discussed under (4) above.

Given the wide diversity of stratigraphical changes seen in this study, it is likely that many of these factors have been operative and possibly interacting to influence the observed biostratigraphical and geochemical patterns and the rates and magnitudes of biotic change. Deposition of atmospheric contaminants such as SCPs, PAHs, PCBs, and possibly Pb from both long-range and local sources is recorded in Svalbard lake sediments in the last 30 - 40 years. It does not appear, however, to have had any major ecological impacts except possibly on chrysophyte cyst assemblages. Differences in the composition of cyst assemblages in 'top' and 'bottom' sediment samples (Betts-Piper et al. 2004) suggest that the pH of lakes on acid bedrock may have decreased whereas the pH and conductivity of lakes on more base-rich bedrock may have increased. Betts-Piper et al. (2004) propose that Svalbard lakes, being located on deep permafrost, are likely to be particularly sensitive to acid precipitation as there is little ground-water interaction. Increased melting of snow and ice in spring due to the increasing spring temperature and precipitation since 1912 (Førland et al. 1997; Hanssen-Bauer and Førland 1998) may have resulted in sudden pulses of acidic meltwater causing a decrease in lake pH (cf. Lien et al. 1993, 1995). The effects of these 'spring shocks' may have been short-lived and as many chrysophytes are spring blooming they would be sensitive to sudden drops in pH. With warmer and wetter springs and summers since 1912, rates of chemical weathering and mineral dissolution may have increased and sites on non-acid bedrock would thus receive an increase in base cations, resulting in an increase in pH and conductivity in recent times, as reflected by the changes in the cyst assemblages at lakes A and B.

Atmospheric deposition of nitrogen compounds has doubled in the last 100 years in northern and arctic Europe (Neftel et al. 1985; Laj et al. 1992). Human alteration of the global nitrogen cycle has doubled the amount of fixed nitrogen, particularly as NH_4^+ and NO_3^-, transferred from the atmosphere to land-based ecosystems (Vitousek et al. 1997). Precipitation rates also determine nitrogen deposition values (Tørseth and Semb 1997). The levels of deposition of nitrogen compounds on Svalbard, as measured near Ny-Ålesund in the last 20 years (Tørseth 1996; Beine et al. 1996; AMAP 1997), are very low, as are stream- and lake-water values for NO_3-N and NH_4-N for 162 localities throughout Svalbard (Lien et al. 1993, 1995). The low surface-water values (6 – 8 μeq l^{-1}) are particularly relevant because, as Lien et al. (1993, 1995) note, the bulk of atmospherically deposited nitrogen is expected to find its way into surface waters. With the low vegetational cover, the widespread occurrence of permafrost, the short growing season, and low temperatures, only a small amount of the atmospherically deposited nitrate and ammonium is expected to infiltrate into the soil and to be retained by the vegetation. After oxidation of ammonium, most of the deposited nitrogen will appear in surface waters as nitrate. On Svalbard, nitrogen compounds account for about 10% of the atmospheric contaminants, compared with 90% represented by sulphur compounds (Lien et al. 1993, 1995). Little is known about the nutrient limitations of algal growth and productivity in high Arctic lakes. However, Maberly et al. (2002) have shown for 30 upland lakes (125 – 528 m elevation) in the British Isles that they are equally likely to be nitrogen- or phosphorus-limited or most likely to be co-limited by both. Nitrogen-fixing cyanobacteria, which are relatively slow growing, appear to be unable to thrive in upland lakes where pH and phosphorus concentration are low and where flushing rates tend to be high (Maberly et al. 2002). Terrestrial ecosystems on Svalbard are strongly nitrogen- and phosphorus-limited (Gordon et al. 2001). With recent climate warming, soil temperatures rise, and rates of mineralisation are likely to increase, potentially increasing nitrogen and phosphorus availability to terrestrial vegetation. Thus recent climate changes with increasing temperatures and increased growing season may increase nitrogen utilisation by terrestrial vegetation and consequently decrease the nitrogen input into surface waters. There is no evidence from the Svalbard palaeolimnological records for any impacts or responses resulting from atmospheric deposition of nutrients, such as nitrogen, from atmospheric sources.

Climatic change may have been important in influencing sediment accumulation rates. The systematic increases in sedimentation rates (Appleby 2004) may be a response to increased production and inwash of catchment material resulting from recent climatic shifts. The episodic events in sediment accumulation rates seen at some of the Svalbard lakes may have resulted from short-lived increases in precipitation, causing increased inwash of clastic material or from human impact in the lake's catchment, especially at Tenndammen (U). Human activity and subsequent abandonment appear to have also been important in influencing the chironomid compositional changes at Tenndammen (Brooks and Birks 2004).

The chironomid stratigraphies at Ossian Sarsfjellet (C) and Ytertjørna (Q) and the diatom stratigraphies at Arresjøen and Birgervatnet all show major shifts in composition that appear to be unrelated to independent evidence for atmospheric contamination. There is no independent evidence for any human impact in the catchments of these lakes. The major biostratigraphical changes are possibly related to the onset and the end of the 'Little Ice Age' and subsequent recent climatic change. The statisticaly significant increases in the rate of compositional change (Figure 5) may be a response to recent climate change, to recent increases in the deposition of atmospheric nitrogen compounds, or to a combination of both, in the last 50 years.

Although the nutrient signal in the modern diatom data-set is weak, stratigraphical evidence at Ytertjørna (Q) and Arresjøen (Figure 3c) suggests a small but decreasing trend in nutrients (Jones and Birks 2004), arguing against the possible importance of the input of atmospheric nitrogen compounds. The chironomid stratigraphies suggest that over the last 200 years the trophic status of Ossian Sarsfjellet (C) decreased whereas the trophic status may have increased at Ytertjørna (Q) (Brooks and Birks 2004). These varied biotic responses between and within lakes (or lack of any major responses as shown by the diatom stratigraphy at 'Scurvy Pond' and Vassauga (S) both of which are dominated by *Fragilaria* species) illustrate the strongly individualistic lake and catchment response to the end of the 'Little Ice Age' and recent climatic shifts, including associated changes in catchment productivity, biota, and clastic yield. Within Svalbard there is so much geological diversity that almost every lake studied is different environmentally and biologically. This is shown by the different positions of the chironomid and diatom stratigraphies in the combined DCAs of the modern and fossil samples and the wide dispersion of the modern samples (Figures 3a and 4a). The combined DCA of the diatom samples shows that the fossil stratigraphies are similar at the three strandflat lakes studied where *Fragilaria* species dominate and at the two deep sites (Arresjøen and Birgervatnet) (Figure 3a). Otherwise almost every biostratigraphic record, although covering the same time period of the last few hundred years, is different in composition and assemblage shifts. Despite these compositional differences between sites, there are striking similarities in the rate of compositional change in all the sequences in the last 400 years, with a marked increase in the rate of change in the last 50 - 100 years (Figure 5). This increase is unprecedented in the context of the last 500 - 800 years.

Similar high rates of composition change and/or marked shifts in assemblage composition have been found from palaeolimnological studies in the Canadian Arctic (e.g. Douglas et al. 1994; Gajewski et al. 1997; Rühland et al. 2003; Overpeck et al. 1997; Wolfe and Perren 2001; Michelutti et al. 2003), the Finnish Arctic (Sorvari and Korhola 1998; Sorvari et al. 2002), and elsewhere on Svalbard (S. Holmgren pers. commun.). Increases in sediment accumulation rates and/or biogenic silica in the last 50 - 100 years have also been reported from the Canadian Arctic (Hughes et al. 2000) and southern Greenland (Kaplan et al. 2002). These abrupt limnological changes are all interpreted as responses to recent warming trends. Such trends could lead to a longer growing season and extended ice-free periods that can influence lake-water chemistry, increased littoral habitat availability, thermal stratification patterns, aquatic biota, and within-lake productivity (Rühland et al. 2003). Increased duration and stability of thermal stratification with climatic warming may influence pH, alkalinity, and nutrient and light availability (e.g. Rühland et al. 2003; Sorvari and Korhola 1998; Sorvari et al. 2002). Although there are distinct changes in diatom and chironomid composition in the last 50-100 years at some sites on Svalbard, all sites show a statistically significant increase in the rate of compositional change in the last 50 - 100 years (Figure 5). The most likely cause of this accelerated rate of change at all sites is recent climatic change, leading to decreased lake ice-cover, longer growing seasons, and greater habitat availability. Human activity was also an important causal factor at Tenndammen (U). The increases in organic matter accumulation in the uppermost samples at Ytertjørna (Q), Vassauga (S), and Daltjørna (T) discussed by Boyle et al. (2004) may similarly reflect, in part, recent limnological responses to climate change in the last 40 - 50 years.

Conclusions

Besides revealing a wide range of sedimentary and biological changes in Svalbard lakes over the last few hundred years, our study has highlighted many problems of applying palaeolimnological techniques to high Arctic lakes. These problems include very low sediment accumulation rates (0.02 - 0.10 cm y^{-1}), making detailed fine-resolution analysis very difficult, especially fine-resolution sampling under demanding field conditions. There is considerable and unpredictable variation from site to site and from taxonomic group to taxonomic group in the concentration and preservation of different fossils, with the result that diatom and chironomid stratigraphies could only be developed for one site (Ytertjørna) but even there chrysophyte cysts were not countable in the 'bottom' sediment sample. Taxonomic problems arise, particularly with diatoms, when 15% of the taxa found cannot be assigned to previously described forms (Jones and Birks 2004). There is very low diversity in some taxonomic groups such as chironomids. There is very limited knowledge of high Arctic limnological and sedimentary processes and of the ecology of the taxa concerned, resulting in difficulties in interpreting some of the stratigraphical patterns. In studying atmospheric contamination, problems arose because the contamination levels are close to current 'detection limits'. This is especially a problem for heavy metals where the natural background levels of heavy metals are high and very site-specific, making it difficult to detect unambiguously any atmospheric contamination. The lakes are thus insensitive long-term monitors of heavy metal inputs. The geochemistry of the sediments shows great differences in major elements between sites. Reasons for the high background levels of some PAHs and PCBs (Rose et al. 2004) are unknown. The last problem, possibly a feature of Svalbard rather than the high Arctic as a whole, is there is very considerable lake individualism, possibly resulting from a complex of factors including catchment geology, size, productivity, and topography, lake size and depth, and landform. As a result of this individualism, there are few consistent stratigraphical patterns in terms of inferred environmental change or biotic shifts. The major consistent biological patterns to emerge are the increased rates of compositional change in the last 50 years. It is clear that Svalbard lakes and their biota are highly dynamic and many have been showing marked changes in biota, sedimentation, and geochemistry over the last 100 - 200 years. Svalbard lakes and catchments appear to be highly dynamic systems that are showing marked biotic and sedimentary responses to recent environmental change, in common with many lakes elsewhere in the Arctic. High Arctic lakes and their sedimentary records provide a unique historical record of recent biotic and environmental change in the Arctic.

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