The dynamics of Chironomidae (Insecta: Diptera) assemblages in response to environmental change during the past 700 years on Svalbard*

Stephen J. Brooks[1] & H.J.B. Birks[2]

[1] *Department of Entomology, The Natural History Museum, Cromwell Road, London SW7 5BD, UK*

(E-mail: s.brooks@nhm.ac.uk)

[2] *Botanical Institute, University of Bergen, Allégaten 41, N-5007 Bergen, Norway and*

Environmental Change Research Centre, Department of Geography, University College London, 26 Bedford Way, London WC1H 0AP, UK

(E-mail: John.Birks@bot.uib.no)

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Abstract

The impact of recent natural and human-induced environmental change on chironomid faunas on Svalbard has been investigated. The modern chironomid fauna was studied from surface-sediment samples collected from 23 lakes in western Svalbard. A total of 18 taxa was found, of which three had not been recorded previously from Svalbard. The influence of water chemistry and physical variables on the distribution and abundance of the modern chironomid assemblages was investigated using correspondence analysis (CA) and multiple regression. The chironomid assemblages fall into four groups, which are primarily influenced by pH, nutrient concentrations, water temperature, and water depth. Sediment cores were taken from three lakes to investigate changes in chironomid assemblages over the last 700 years. At two of the sites there is evidence for a response to regional climatic change occurring about 200 years ago and may have been associated with the 'Little Ice Age'. At the third site there is a response to local catchment changes, probably brought about, initially, by the establishment of a human settlement close to the lake 70 years ago, and subsequently, as a result of the abandonment of this settlement in 1988.

Introduction

The negative impact of human activities on the environment is of growing concern as ecosystems are increasingly degraded, as restoration costs escalate, and as land-use becomes unsustainable. However, an understanding of the impact of natural environmental change on ecosystems is an essential background against which the extent of anthropogenic-induced change can be assessed. Pristine environments are the most appropriate places to detect the effects of natural environmental change, but such environments can only be found at extremes of altitude and latitude, far from human influences. One such place is Svalbard (74 - 81°N), which has only a small resident human population and is apparently remote from the effects of atmospheric pollution (Rose et al. 2004).

In this study on the islands of Svalbard, we are interested to see if we can detect ecosystem responses to small-amplitude natural climatic changes that have occurred over the last 700 years. We are especially interested in looking for a response to the 'Little Ice Age' (LIA) (Grove 1988), which may have begun 500 - 600 years ago, during which glaciers reached their Holocene maximum extent, and lasted until the mid-19th or early 20th century (Svendsen and Mangerud 1997). We also want to see if human activities, either local or remote, have impacted the environment. One indicator group chosen to reflect environmental change is non-biting midges (Insecta: Diptera: Chironomidae) that are very sensitive to changes in freshwater ecosystems (Lindegaard 1995). Chironomids are particularly amenable to palaeolimnological studies (Walker 1995) and have been used to quantify past changes in air temperature (Lotter et al. 1997, 1999; Olander et al. 1999; Brooks and Birks 2000a, 2000b; Larocque et al. 2001), total phosphorus (Brooks et al. 2001), dissolved oxygen (e.g. Clerk et al. 2000), and salinity (Walker et al. 1995), and are also known to respond to changes in pH (e.g. Henrikson and Oscarson 1985; Brodin and Gransberg 1993). In addition to chironomids, other methods have been used in this study to investigate recent environmental change on Svalbard (Jones and Birks 2004; Betts-Piper et al. 2004) and a synthesis of the results is presented in Birks et al. (2004a).

Figure 1. Map showing the location of the 21 lakes (A-U) visited in 1995, the 3 lakes (Arresjøen, Birgervatnet, 'Scurvy Pond') visited in 1993, and the major settlements on Spitsbergen. The inset map shows the location of Svalbard in relation to Greenland, Iceland, Fennoscandia, the United Kingdom (UK), and the North Pole. Modern chironomid assemblages were studied from all lakes except L, and fossil chironomid assemblages were studied at lakes C, Q, and U.

Methods

Surface-sediment samples were collected from 23 lakes in western Svalbard (Figure 1) using a modified Kajak-Brinkhurst gravity corer (Glew 1989). The uppermost 1 cm was retained for analysis to characterise the modern chironomid assemblage of each lake. In addition, sediment cores of up to 25 cm were collected from three lakes (Ossian Sarsfjellet (C), Ytertjørna (Q), and Tenndammen (U)), and sliced at 1 cm intervals to study the dynamics of the chironomid assemblages in the recent past. Full site descriptions and details of water chemistry and physical attributes of each lake are given in Birks et al. (2004b). Major features of lakes C, Q, and U are summarised in Table 1.

Table 1. Major environmental features of the three lakes (C, Q, and U) from which sediment cores were studied. For further details, see Birks et al. (2004b).

Lake	Altitude (m)	Water depth (m)	pH	Total P (μg l^{-1})	Conductivity (μS cm^{-1})
Ossian Sarsfjellet (C)	60	26	8.0	4.3	153
Ytertjørna (Q)	20	2.6	7.9	7.5	153
Tenndammen (U)	5	2.5	7.1	4.4	323

For chironomid analysis, wet sediment samples were deflocculated for 15 minutes in 10% KOH, warmed to 75°C, and passed through 212 μm and 90 μm sieves. The residue was transferred to a grooved perspex sorting tray (Bogorov sorter with groove 5 mm deep, 5 mm wide), and at least 50 chironomid larval head capsules were picked out with fine forceps under a x 25 binocular microscope. The head capsules were dehydrated in 100% ethanol and slide mounted, ventral side up, in Euparal. Head capsule concentrations are based on numbers per gram of wet sediment.

The head capsules were identified with reference to Cranston (1982), Hofmann (1971), Rieradevall and Brooks (2001), Moller Pillot and Buskens (1984), Schmid (1993), Wiederholm (1983), and the National Collection of Chironomidae housed at the Natural History Museum, London. The relative abundance of each chironomid taxon within each sample is presented as a percentage diagram constructed using TILIA-GRAPH 1.18 (Grimm 1991). Zones, defined by major changes in chironomid assemblage composition, were identified by constrained sum-of-squares cluster analysis (Grimm 1991). Sediment loss-on-ignition (LOI) at 550°C is plotted with the stratigraphical data, along with ^{210}Pb dates and an estimated sediment chronology for each core (Appleby 2004).

Ordinations were performed using the program CANOCO 3.12a (ter Braak 1991). The influence of water chemistry and physical and catchment variables on the distribution and abundance of modern chironomid taxa was investigated by an indirect gradient analysis approach involving correspondence analysis (CA), with down-weighting of rare taxa, no rescaling or detrending, and strict convergence criteria on square-root transformed taxon percentage data (ter Braak 1987) and subsequent multiple regression of the water chemistry, physical, and catchment variables on the CA axes. Forward selection (ter Braak 1990) was performed to identify which environmental variables explained a statistically significant ($p \leq 0.05$) amount of variation in the modern chironomid data. The significance of each variable was tested using unrestricted Monte Carlo permutation tests (999 permutations). This approach of an indirect gradient analysis, in this case CA, followed by regression of potential chemical, limnological, and catchment predictors is used instead of using the direct gradient analytical approach of canonical correspondence analysis because of the small number of lakes (23) in comparison to the number of chemical (14) and limnological and catchment (17) predictor variables. Four groups of modern chironomid assemblages were delimited on the basis of the lake scores on CA axes 1 and 2.
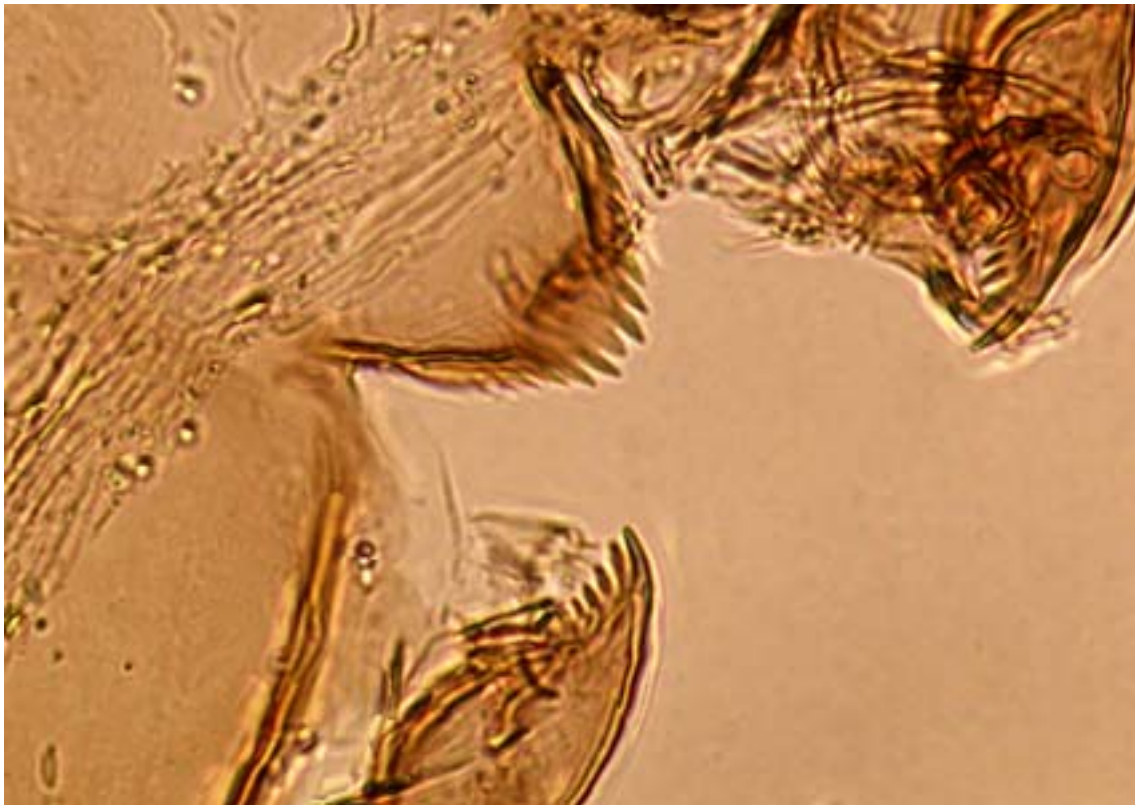

Figure 2. Larval head capsule in ventral view of *Diamesa* cf. *zernyi* Edwards.

Results and discussion

Taxonomic notes

Lindegaard (1997) lists 60 species in 20 genera of Chironomidae from Svalbard, Bjørnøya, and Jan Mayen Island. Most of the taxa recorded during the present study are on this list. However, there are three that are recorded for the first time. *Tanytarsus lugens*-type was found in surface-sediment samples from seven lakes with an abundance of 5 - 20% and also down-core at two lakes. In addition, neither *Zavrelimyia* nor *Corynoneura scutellata*-type has been recorded previously from Svalbard, although both taxa occur at low abundance in the down-core samples. Since neither taxon was found in any of the surface-sediment samples it is possible that they both have become extinct in Svalbard in recent decades.

Diamesa cf. *zernyi* Edwards (Figure 2) is distinguished from *Diamesa* cf. *arctica* (Boheman) by the reduced number of lateral teeth on the mentum (6 teeth) and the three prominent median teeth. The taxon resembles the figure of *D. zernyi* Edwards given by Schmid (1993) but *D. zernyi* has not been recorded previously from Svalbard. However, *D. bohemani* Goetghebuer and *D. hyperborea* Holmgern, which belong to the *D. zernyi* species-group, are known from Svalbard (Lindegaard 1997).
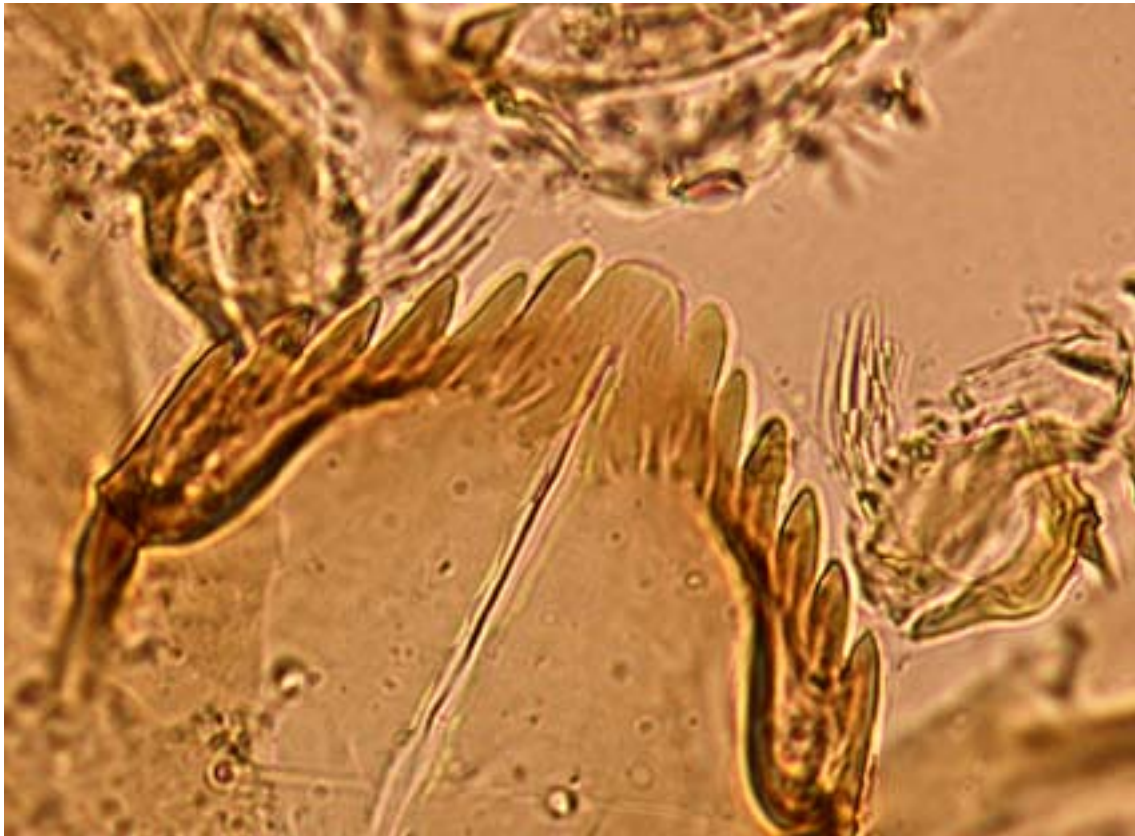

Figure 3. Larval head capsule in ventral view of *Orthocladius trigonolabis* Edwards-type.

Orthocladius trigonolabis Edwards-type (Figure 3) is distinguished from other *Cricotopus* and *Orthocladius* species by the relatively long and narrow first and second lateral teeth on the mentum. In most species in these genera the second lateral teeth are shorter than the other laterals and the first laterals are relatively broad. In many species of *Cricotopus* and *Orthocladius* the outer margins of the mandibles are grooved but in *Orthocladius trigonolabis*-type the outer margins of the mandibles are smooth. The premandibles have a single apical tooth.

The mentum of *Oliveridia* resembles *Hydrobaenus conformis* (Holmgren) but differs in the shape of the ventromental plates. In *Oliveridia* (Figure 4) the ventromental plates are narrow and acute at the apices, and the head capsule is usually pigmented dark brown. In *Hydrobaenus conformis* (Figure 5) the ventromental plates are broader and rounded apically, and the head capsule is pale yellow. The figure of *Oliveridia* in Weiderholm (1983) depicts a specimen with a single median tooth on the mentum. However, the figured specimen is worn and many specimens referable to the genus can be expected to have a paired median tooth (Schnell 1998).
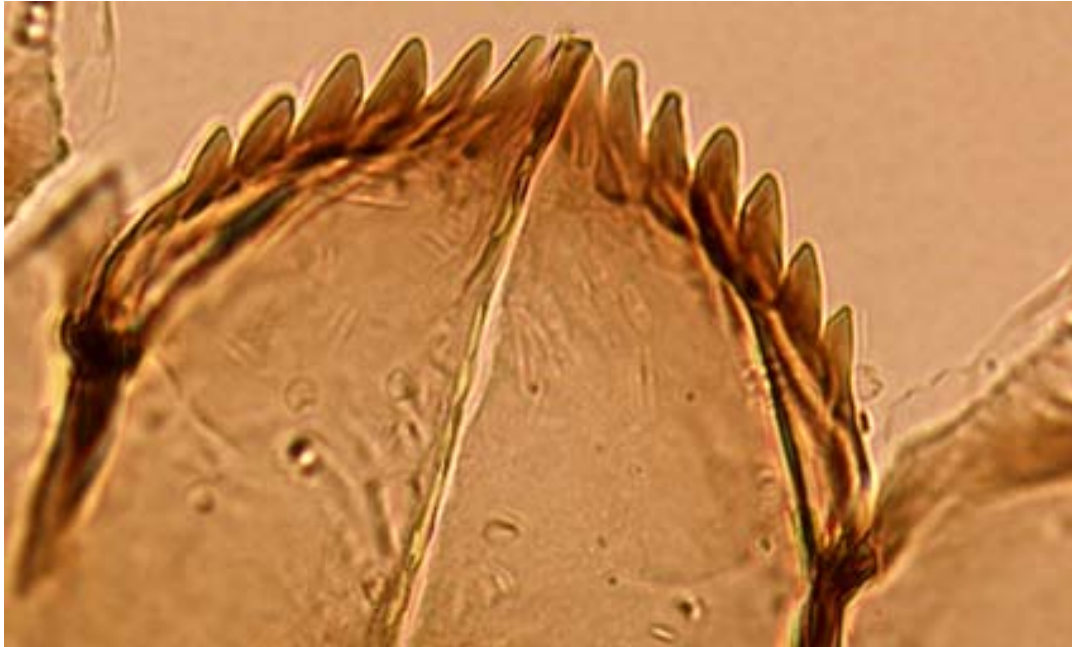

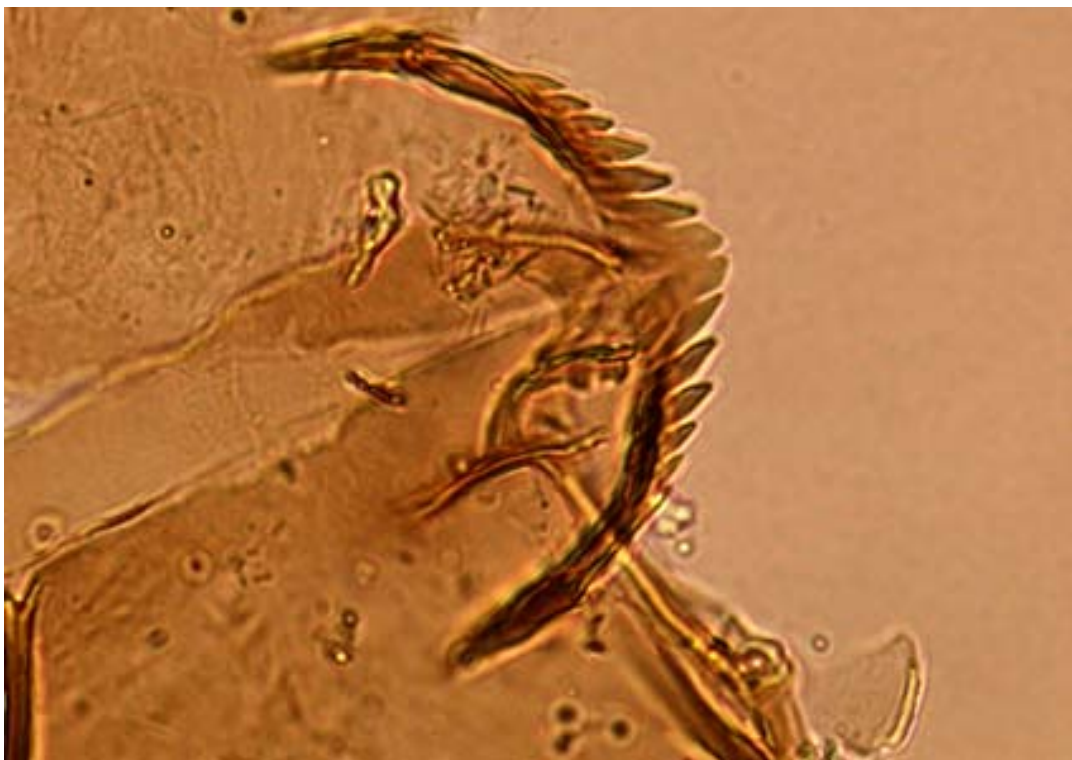*Figure 4*. Larval head capsule in ventral view of *Oliveridia*.

Figure 5. Larval head capsule in ventral view of *Hydrobaenus conformis* (Holmgren).

Surface-sediment analysis

Ordination

Regression onto the CA axes of the modern chironomid assemblages was performed with the water chemistry and physical and catchment data separately because the total number of predictor environmental variables (31) was greater than the number of lakes (23) sampled. The eigenvalues for CA axis 1 (0.44) and CA axis 2 (0.38) explain 48.6% of the total variance ('inertia') of the chironomid assemblages. The species-water chemistry correlations for axes 1 and 2 are 0.64 and 0.90, respectively, and account for 45.7% of the variance in the chironomid-environment relationship (Table 2). The species-lake and catchment variables correlations for CA axes 1 and 2 are 0.81 and 0.98, respectively, and account for 48.6% of the variance in the chironomid-environment relationship (Table 3).

Table 2. Summary statistics for the first four CA axes with 23 sites, 18 chironomid taxa, and 14 water chemistry variables. Taxon data were square-root transformed and rare taxa downweighted.

CA axes	1	2	3	4
Eigenvalues	0.44	0.38	0.20	0.17
Species-environment correlations	0.64	0.90	0.95	0.82
Cumulative % variance				
- of taxon data	26.2	48.6	60.4	70.7
- of taxon-environment relationship	17.1	45.7	62.6	73.5
Total variance (= 'inertia') 1.68				

Table 3. Summary statistics for the first four CA axes with 23 sites, 18 chironomid taxa, and 17 physical variables. Taxon data were square-root transformed and rare taxa downweighted.

CA axes	1	2	3	4
Eigenvalues	0.44	0.38	0.20	0.17
Species-environment correlations	0.81	0.98	0.93	0.85
Cumulative % variance				
- of taxon data	26.2	48.6	60.4	70.7
- of taxon-environment relationship	21.4	48.6	61.5	71.1
Total variance (= 'inertia') 1.68				

In forward selection, the only water chemistry variable that explains a statistically significant ($p < 0.05$) amount of variation in the chironomid data is pH (p-value = 0.023). With forward selection, two limnological and catchment variables explain a statistically significant ($p < 0.05$) amount of variation in the chironomid data. These are strandflat situations (p-value = 0.004) and surface-water temperature (p-value = 0.028).

Figures 6 and 7 present biplots of the CA ordinations based on 18 chironomid taxa, 23 sites, and 14 water chemistry or 17 lake and catchment variables, respectively. In Figure 6, CA axis 2 contrasts relatively productive, high pH lakes at the bottom of the diagram with more oligotrophic, acidic lakes in the upper half. In Figure 7, CA axis 1 places cold-water lakes with a high percentage of snow cover in their catchments to the right of the diagram. CA axis 2 relates to water depth, with the deeper lakes in the upper part of the diagram and shallower, strandflat ponds in the lower part of the plot.
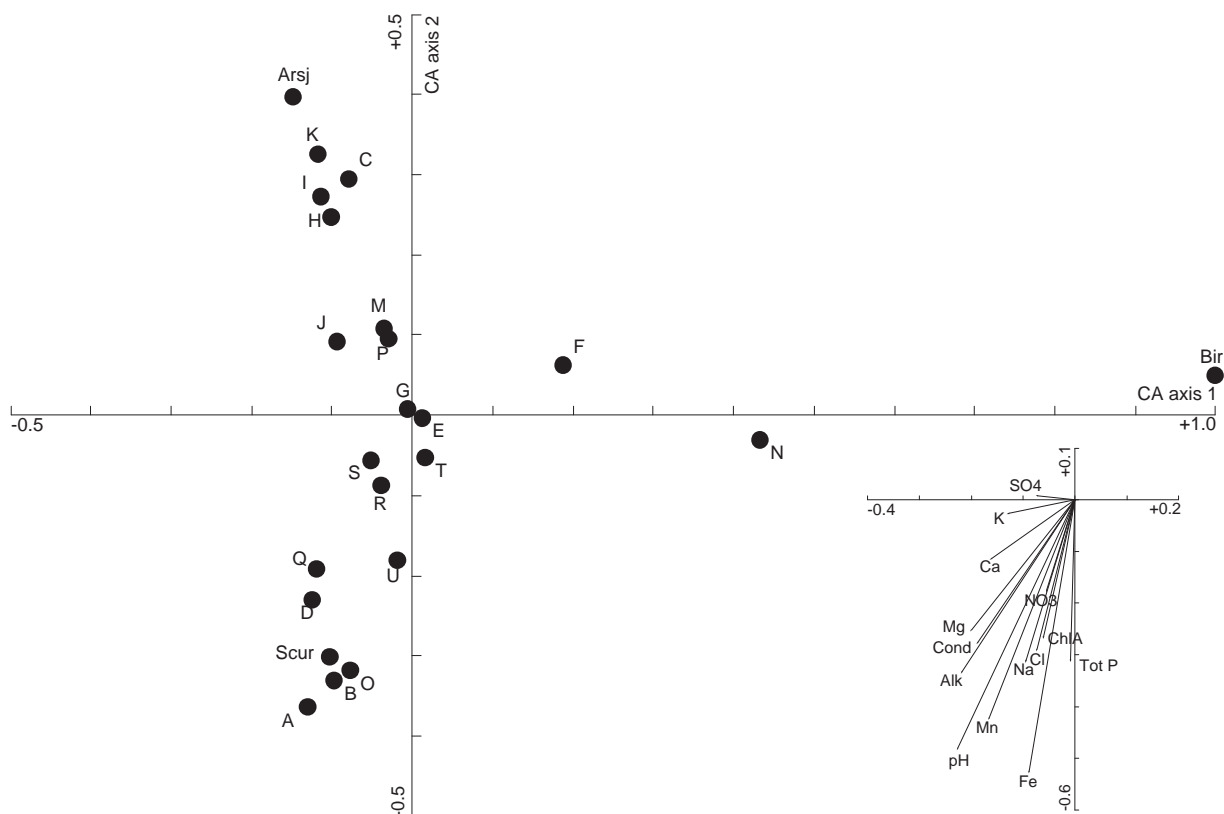
Figure 6. Biplot of correspondence analysis (CA) axes 1 and 2 with 23 sites and 14 water chemistry variables (inset plot). Biplot scaling with taxon scores as weighted mean site scores (ter Braak, 1990). Arsj = Arresjøen, Scur = 'Scurvy Pond', Bir = Birgervatnet, Cond = conductivity, Alk = alkalinity, ChlA = chlorophyll *a*, Tot P = total dissolved phosphorus, NO3 = NO_3^-.

Chironomid analysis

A total of 18 taxa was recorded from surface-sediments of the 23 lakes sampled. The distribution of these taxa and their relative abundance in the fauna of each lake are shown in Figure 8. With the exception of *Diamesa zernyi*-type and *Sergentia*, all are also found in at least one of the down-core samples discussed below. With the exception of *Zavrelimyia* which is found in the Ossian Sarsfjellet (C) core and *Corynoneura scutellata* Winnertz-type in the Tenndammen (U) core, the surface samples include all taxa that occurred in the down-core samples.

Based on overall similarities in their modern chironomid assemblages, the lakes fall into four groups (Figure 8), as delimited from the CA plots (Figures 6 and 7).

Group 1 includes lakes F, N, and Birgervatnet, which are spread out along CA axis 1 on the right of the biplots (Figures 6 and 7). All three lakes are dominated by *Oliveridia*. This is the only taxon found in the glacier-fed Birgervatnet. Lake N differs from the other sites in having a sizeable proportion of *Diamesa* spp.

Group 2 includes lakes C, H, I, K, and Arresjøen. They all appear close to CA axis 2 at the upper left of the biplots (Figures 6 and 7). These lakes are dominated by *Micropsectra radialis*-type (40 - 95%) with *Orthocladius consobrinus* (Holmgren)-type (0 - 5%) in low abundance. Another characteristic feature of the fauna is that *Psectrocladius sordidellus* (Zetterstedt)-type is absent.

Group 3 includes lakes G, J, M, and P, all of which appear near the origin of the biplots (Figures 6 and 7). These lakes support *Orthocladius consobrinus*-type at 30 - 40% (5% in the case

of lake P), *Micropsectra radialis* Goetghebuer-type between 35 - 65%, and *Paratanytarsus austriacus* (Kieffer)-type present at an abundance of 5 - 10%.
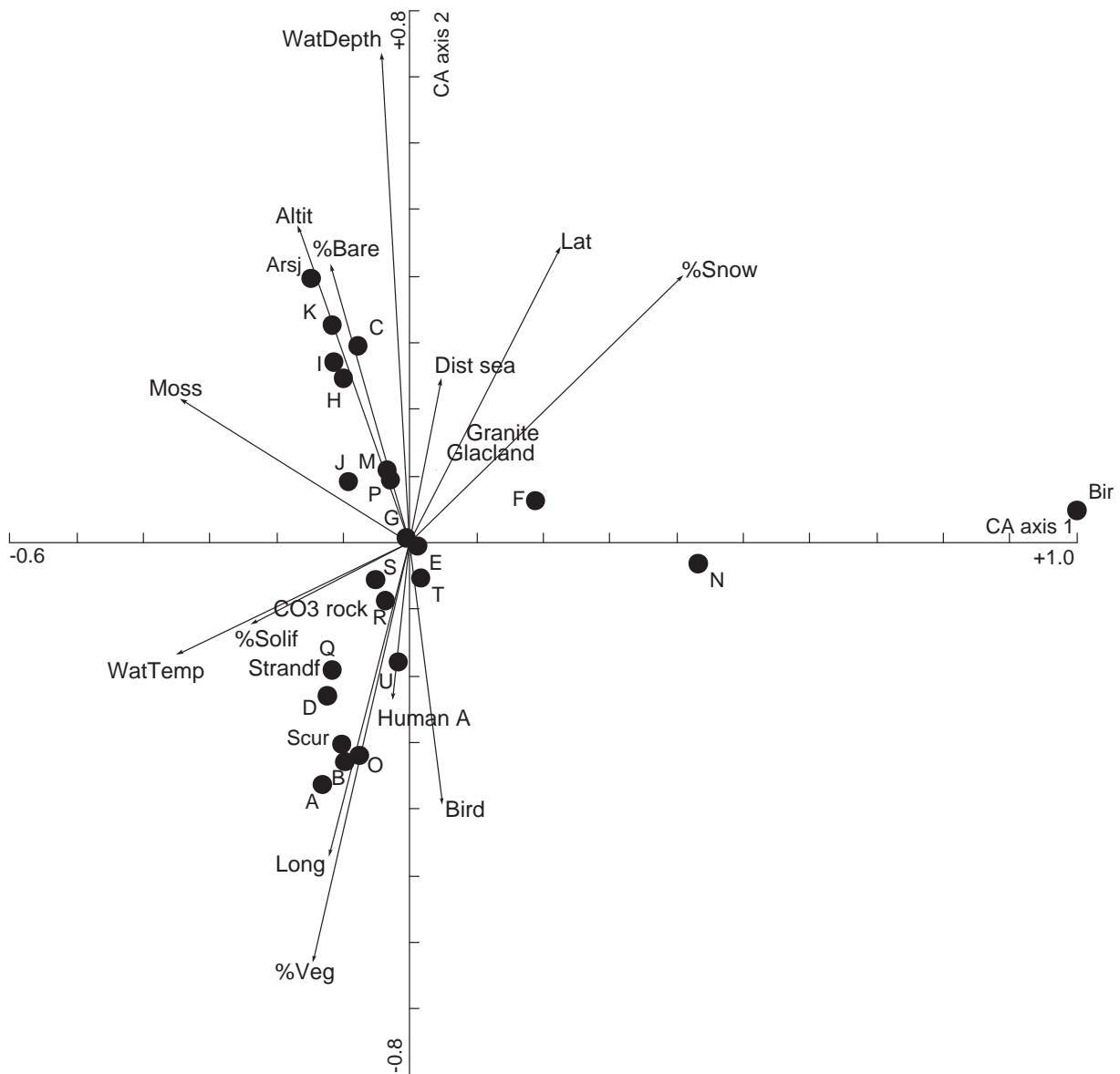

Figure 7. Biplot of CA axes 1 and 2 with 23 sites and 17 lake and catchment variables. Scaling and abbreviations as in Figure 5. WatDepth = water depth, Altit = altitude, %Bare = percentage of bare ground in catchment, Dist sea = distance from sea, Lat = latitude, %Snow = percentage of snow in the catchment, Glacland = glaciated landscape, WatTemp = water temperature, CO3 rock = carbonate rock, Strandf = strandflat landscape, Human A = human activity, Long = longitude, Bird = bird presence, %Veg = percentage of vegetated ground in catchment, %Solif = percentage of solifluction and patterned ground in catchment.

Group 4 includes lakes A, B, D, E, O, Q, R, S, T, U, and 'Scurvy Pond' which fall in the bottom left of the CA biplots (Figures 6 and 7). They are dominated by *Orthocladius consobrinus*-type (>30 - 95%) with *Micropsectra radialis*-type absent or <25%. Lakes A, B, O, Q, and 'Scurvy Pond' do not have *Paratanytarsus austriacus*-type, but this taxon is present at 5 - 25% in the other lakes in this group. Lake U has a distinctive fauna with a higher abundance of *Limnophyes*, *Metriocnemus*, and *Smittia* than other lakes examined and is also the only site that supports *Chironomus anthracinus* Zetterstedt-type.
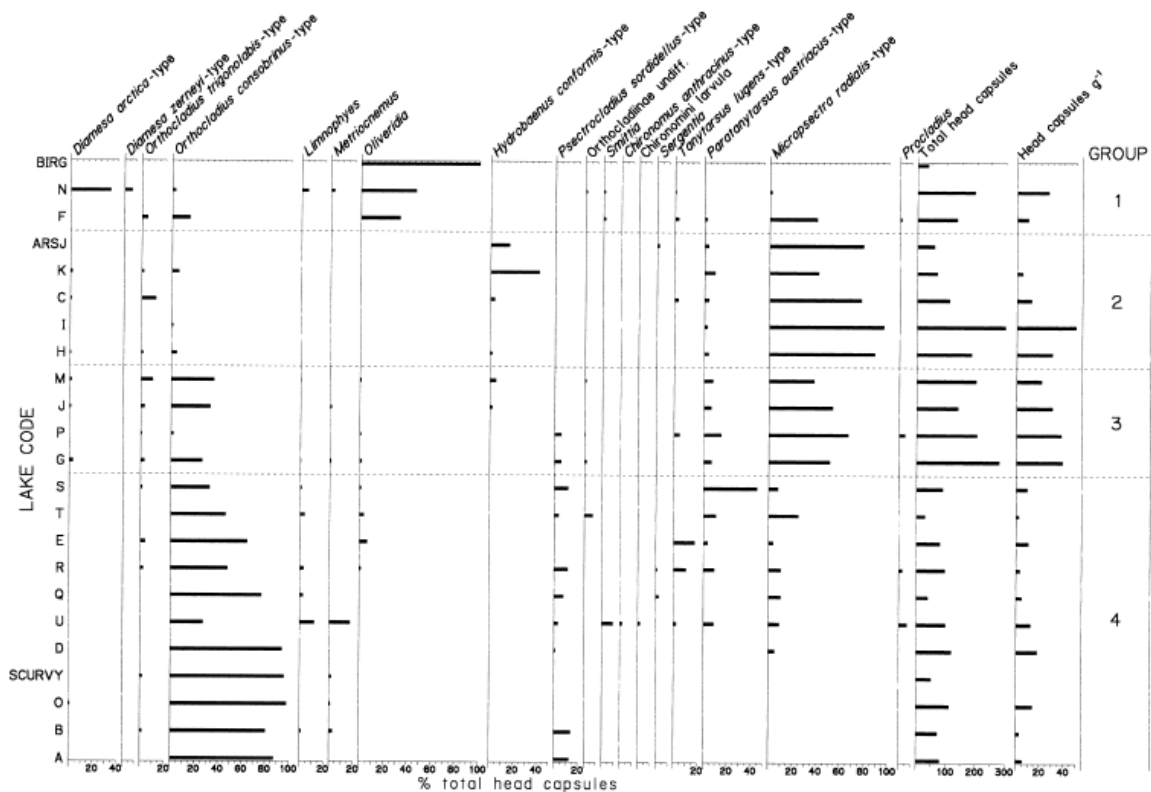
Figure 8. Percentage abundance of chironomid taxa in the surface sediments of 23 lakes in western Svalbard. The lakes are ranked according to their CA axes 1 and 2 sample scores. The full names and descriptions of each lake are given in Birks et al. (2004a). Birg = Birgervatnet; Arsj = Arresjøen.

Ecological interpretation and comparison with diatom results

The lake groupings, based on the similarities of their modern chironomid assemblages, broadly resemble the diatom-based lake groups (Jones and Birks 2004), although in the CA biplots (Figures 6 and 7) the chironomid-based groups are not as discrete as the diatom-based lake groups. Most of the lakes in Group 4 (Figure 8) are the same as those grouped together in the bottom left of the diatom biplot and are all shallow, strandflat ponds, with relatively high pH and nutrient concentrations (Figures 6 and 7). These lakes are frequented by large numbers of sea-birds whose contribution of guano may be an important factor explaining the correlation with nutrients along CA axis 2 (Figure 6). The lakes in this group consistently have the lowest head capsule concentrations of any in the study. This is probably a reflection of the high sediment accumulation rate as a result of high lake productivity that effectively dilutes the head capsules. The distinctive fauna of lake U (Figure 8) is typical of a shallow, nutrient-enriched, disturbed site and it is probably significant that the lake is near to one of the settlements on the island. *Limnophyes*, *Metriocnemus*, and *Smittia* are frequently associated with edge-of-lake, semi-terrestrial or stream habitats, and *Chironomus anthracinus*-type is typical of productive lakes. Most of the lakes in Groups 2 and 3 correspond with the group on the right of the diatom biplot. These lakes vary in size but lie on granite bedrock and are characterised by low pH (Figures 6 and 7). These results suggest that, like the diatom flora, the composition of the chironomid assemblages is influenced, in the past, by water chemistry, in particular pH and nutrient concentrations, but other limnological variables may be important (see Birks et al. 2004a).

However, there are differences in the lake groupings, and lakes C, P, and T have similar diatom floras and are grouped together in the upper left of the diatom CA biplot. The chironomid faunas of these lakes are not so similar and they are separated in the chironomid CA biplots

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(Figures 6 and 7). These lakes are situated in glaciated rock basins, are oligotrophic, with high pH and some are deep (>10 m) (Figure 7). Conversely, lakes F, N, and Birgervatnet have a distinct chironomid fauna, typical of cold, ultra-oligotrophic waters and glacier-fed streams, but have many differences in their diatom flora.

Birks et al. (2004a) compare numerically the various classifications based on different sets of variables (e.g. chironomids, diatoms, water chemistry). They show that the chironomid-based classification is most similar to the classification based on chrysophyte cysts (Betts-Piper et al. 2004) and similar to the classification based on diatoms (Jones and Birks 2004). The biologically based classifications are more similar between themselves than they are between the biological and chemical classifications, suggesting that limnological variables other than water chemistry may be important determinants of the modern biological assemblages.
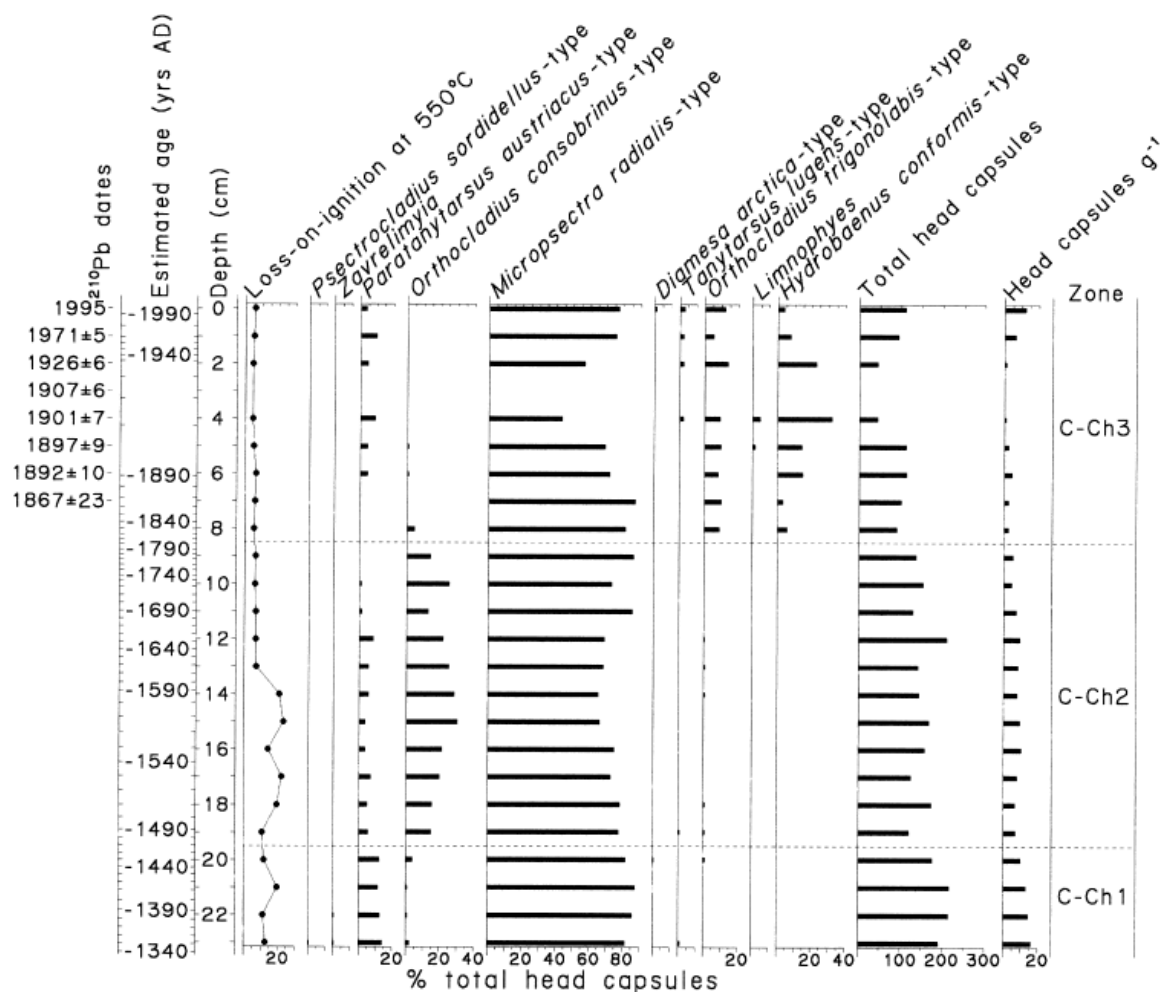

Figure 9. Changes in percentage abundance of Chironomidae in a 23 cm sediment core from Ossian Sarsfjellet (C), Spitsbergen.

Biostratigraphical analysis

Ossian Sarsfjellet (C)

The results of the down-core analysis are shown as a chironomid percentage diagram in Figure 9. Ten chironomid taxa were recovered from this 23 cm core. Three taxa are very rare, each represented by one head capsule below 19 cm (*Diamesa arctica*-type, *Psectrocladius sordidellus*-type, *Zavrelimyia*). One *Diamesa arctica*-type specimen was also found in the top 1 cm. Throughout the core the chironomid fauna is dominated by *Micropsectra radialis*-type which

maintains an abundance of more than 60% in most samples. Three assemblage zones based on changes in the chironomid biostratigraphy are identified by constrained cluster analysis.

Zone C-Ch1 (23.5 - 19.5 cm; 1350 - 1470 AD). This zone is dominated by *Micropsectra radialis*-type (80%) and *Paratanytarsus austriacus*-type (15%) but there are also low numbers of *Diamesa arctica*-type, *Orthocladius consobrinus*-type, *Psectrocladius sordidellus*-type, *Tanytarsus lugens*-type, and *Zavrelimyia*.

Zone C-Ch2 (19.5 - 8.5 cm; 1470 - 1810 AD). This zone is characterised by an increase of *Orthocladius consobrinus*-type to 15 - 20% and a gradual decline to zero of *Paratanytarsus austriacus*-type.

Zone C-Ch3 (8.5 – 0 cm; 1810 - 1995 AD). *Orthocladius consobrinus*-type declines and finally becomes extinct but is replaced by *Orthocladius trigonolabis*-type (10%), *Hydrobaenus conformis*-type (5 - 30%), and *Tanytarsus lugens* Kieffer-type (5%). *Paratanytarsus austriacus*-type reappears in the fauna from 6 cm (5%). There is also a decline in *Micropsectra radialis*-type (to 45 - 55%) between 2 and 4 cm.

Head capsule concentrations gradually decline from zone C-Ch1 to C-Ch3, presumably resulting from increasing sediment accumulation rates and are at their lowest between 2 - 4 cm, above which they increase again to former levels. Numbers of head capsules recovered from the sample at 3 cm were too low to justify analysis.

The marked decline in sediment LOI between 13 and 14 cm (about 1600 AD) does not coincide with any change in the chironomid assemblage.

Ecological interpretation. Figure 10a presents a CA time-track of each sample positioned as passive samples on the CA ordination diagram (Figure 6) with the chemical and other environmental variables fitted by regression (Figures 10d and 10e). The samples fall in the upper left of the biplot which suggests that the lake has remained cool and relatively oligotrophic throughout the period represented, and never became as productive as some of the lakes in the modern surface-sample data-set which appear in the lower left side of the CA scatter plot (Figures 6, 7, and 8). The lowermost samples, corresponding to zone C-Ch1, occupy a middle position in the diagram. During zone C-Ch2, when the lake supported relatively few taxa and *Orthocladius consobrinus*-type was an important element in the fauna, the lake appears to have shifted towards a slightly more productive condition and with a slightly higher pH. Most recently, the position of the upper eight samples (zone C-Ch3, start date about 1810 AD; Appleby 2004) at the top of the diagram suggests that the lake is now in its most oligotrophic condition.

Ytertjørna (Q)

Figure 11 shows the results of the chironomid analysis of this 20 cm core. A total of 12 taxa was recovered from the core that is dominated throughout by *Orthocladius consobrinus*-type and *Micropsectra radialis*-type. Constrained cluster analysis identified three assemblage zones.

Zone Q-Ch1 (20 - 10.5 cm; 1485 - 1830 AD). The lower half of the core is dominated by three taxa namely, *Orthocladius consobrinus*-type (35 - 60%), *Micropsectra radialis*-type (30 - 45%), and *Paratanytarsus austriacus*-type (5 - 25%). There are also sporadic occurrences of *Cricotopus/Orthocladius*, *Limnophyes*, *Metriocnemus*, and *Smittia*.

Zone Q-Ch2 (10.5 - 4.5 cm; 1830 - 1955 AD). In this zone *Orthocladius consobrinus*-type further increases its dominance (65 - 75%), whereas there are concurrent declines in the abundance of *Micropsectra radialis*-type (to 15 - 30%) and *Paratanytarsus austriacus*-type (to <

5%). There is also a marked increase in *Limnophyes* which maintains a presence of about 5% and *Procladius* appears in the fauna.

Zone Q-Ch3 (4.5 - 0 cm; 1955 - 1995 AD). *Orthocladius consobrinus*-type continues to increase (to 70%) while *Micropsectra radialis*-type (to 10 - 25%) and *Paratanytarsus austriacus*-type (from 5 - 0%) continue to decline. There is an abrupt rise in *Psectrocladius sordidellus*-type (to 20%) and several taxa appear for the first time, making this zone the most diverse in the core.

Head capsule concentrations gradually decline towards the top from a maximum at the base of the core.

Ecological interpretation. The CA time-track plot (Figure 10b) and environmental variable ordination biplot (Figures 10d and 10e) show most of the samples in the bottom left side of the diagram, suggesting that the lake remained relatively productive and with a high pH throughout the time represented by the core. There were two distinct phases in the lake's development, changing between 10 and 11 cm, about 1830 AD (Appleby 2004). The CA results suggest that the lake may have become slightly more productive in the upper half of the core.

Tenndammen (U)

The results of the down-core analysis are shown as a percentage chironomid diagram in Figure 12. Head capsule concentrations are very low in certain parts of the core and samples were omitted from the analysis in which less than 50 head capsules were recovered. A total of 14 taxa is present in the core but the fauna is not dominated by any particular taxon. Constrained cluster analysis identified three assemblage zones.

Zone U-Ch1 (17 - 7.5 cm; 1265 - 1930 AD). *Orthocladius consobrinus*-type, *Limnophyes*, *Metriocnemus*, *Smittia*, *Paratanytarsus austriacus*-type, and *Micropsectra radialis*-type each appear at an abundance of 10 - 25%. Other minor elements of the fauna include *Psectrocladius sordidellus*-type, *Chironomus anthracinus*-type, and *Procladius*.
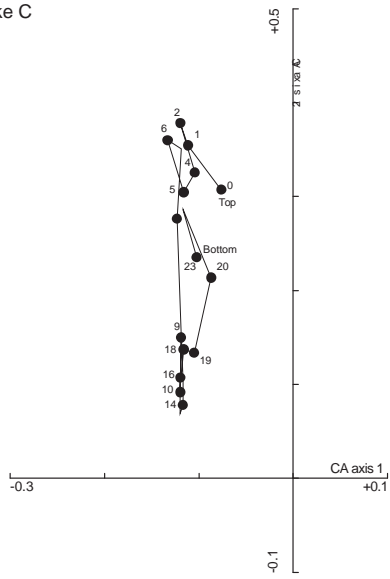
Zone U-Ch2 (7.5 - 1.5 cm; 1930 - 1988 AD). A significant faunal change occurs between 7 - 8 cm with abrupt increases of *Tanytarsus lugens*-type (to 45 - 65%) and *Procladius* (to 10%) together with declines in *Smittia*, *Metriocnemus*, *Chironomus anthracinus*-type, and *Paratanytarsus austriacus*-type (all < 5 - 10%). However, the increase in *Tanytarsus lugens*-type is brief and above 6 cm (ca. 1960 AD) the abundance of this taxon rapidly declines again when there is a steep rise in *Orthocladius consobrinus*-type (to 30%).

Zone U-Ch3 (1.5 - 0 cm; 1988 - 1995 AD). Above 1.5 cm *Smittia*, *Metriocnemus*, *Chironomus anthracinus*-type, and *Paratanytarsus austriacus*-type increase in abundance once more to values closer to those in zone U-Ch1.
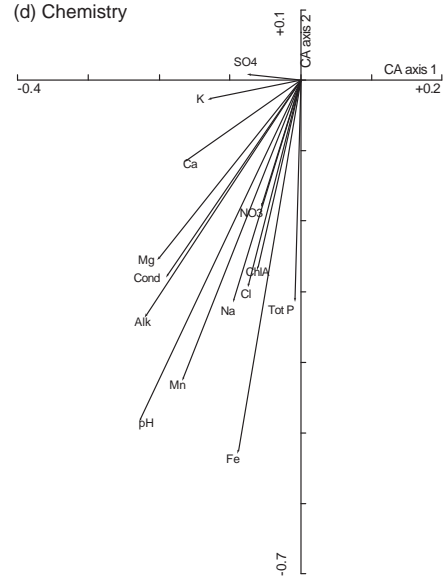
Head capsule concentrations are very low, especially in zone U-Ch1 (below 7 cm) where they remain below 10 head capsules per gram of wet sediment. In zone U-Ch2 concentrations fluctuate considerably, although they are generally higher (10 - 20 g^{-1}) than in zone U-Ch1, although from 2 - 5 cm the concentration falls below 1 g^{-1} and at 1 - 2 cm and 7 - 8 cm concentrations suddenly peak above 40 g^{-1}.

There is a slight rise in LOI values above 8 cm, which coincides with the U-Ch3/U-Ch2 zone boundary, and a steeper rise coinciding with the beginning of zone U-Ch3.
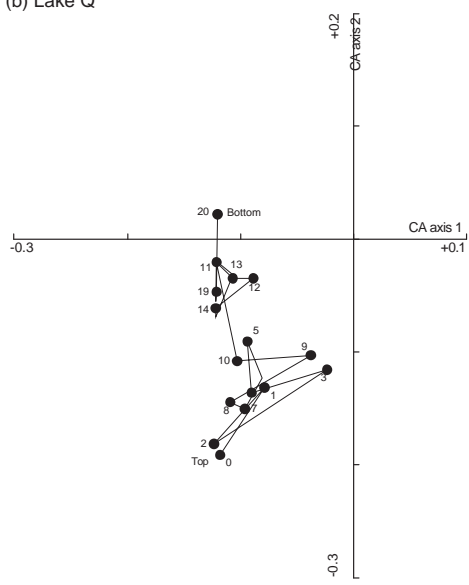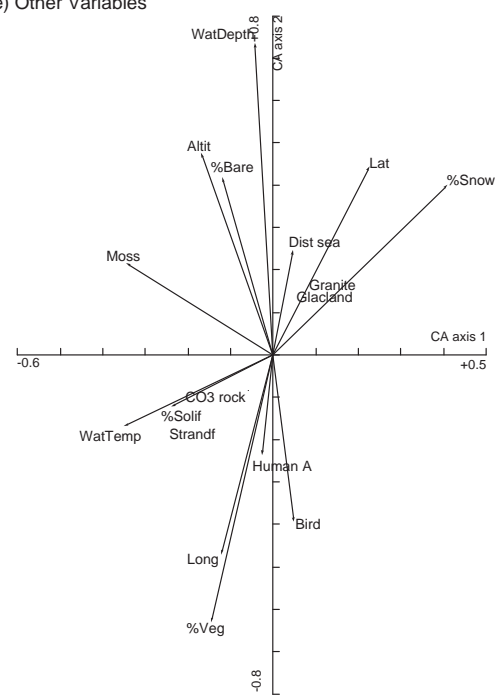
(a) Lake C

CA axis 2

+0.5

2
6
1
4
5
0
Top
Bottom
23
20
9
18
19
16
10
14

CA axis 1
-0.3
+0.1
-0.1

(b) Lake Q

CA axis 2
+0.2

20 Bottom
CA axis 1
-0.3
+0.1

11
13
19
12
14
5
10
9
8
1
3
2
Top
0

-0.3

(c) Lake U

CA axis 2
+0.1

CA axis 1
-0.1
+0.2

9
7
8
5
14
1
6
Top
0
16
17
Bottom
2
15

-0.3

(d) Chemistry

CA axis 2
+0.1

SO4
CA axis 1
-0.4
+0.2
K
Ca
NO3
Mg
Cond
ChlA
Alk
Cl
Na
Tot P
Mn
pH
Fe

-0.7

(e) Other Variables

WatDepth
CA axis 2
0.8

Altit
%Bare
Lat
%Snow
Moss
Dist sea
Granite
Glacland
CA axis 1
-0.6
+0.5
CO3 rock
%Solif
WatTemp
Strandf
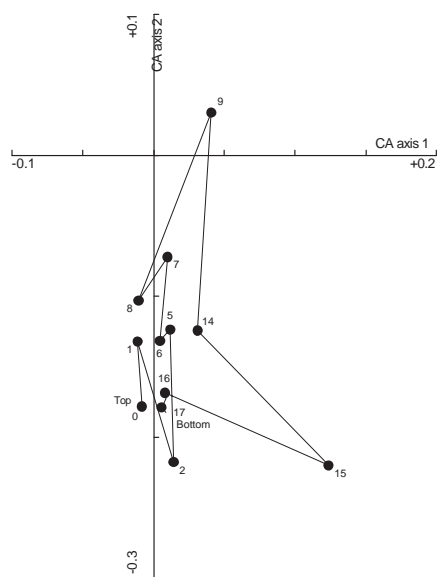Human A
Bird
Long
%Veg

-0.8

14

Figure 10. (a) CA plot of axes 1 and 2 with samples from Ossian Sarsfjellet (C) fitted passively and joined as a time-track to show the changes in the chironomid assemblages in relation to lake chemical and physical variables in the last 650 years. Scaling as in Figure 6. (b) CA plot of axes 1 and 2 with samples from Ytertjørna (Q) fitted passively and joined as a time-track to show the changes in the chironomid assemblages in relation to lake chemical and physical variables in the last 500 years. Scaling as in Figure 6. (c) CA biplot of axes 1 and 2 with samples from Tenndammen (U) fitted passively and joined as a time-track to show the changes in the chironomid assemblages in relation to lake chemical and physical variables in the last 750 years. Scaling as in Figure 6. (d) CA plot of axes 1 and 2 showing the water chemistry variables of Figure 6. Abbreviations follow Figure 6. (e) CA plot of axes 1 and 2 showing the 17 lake and catchment variables of Figure 7. Abbreviations follow Figure 7.
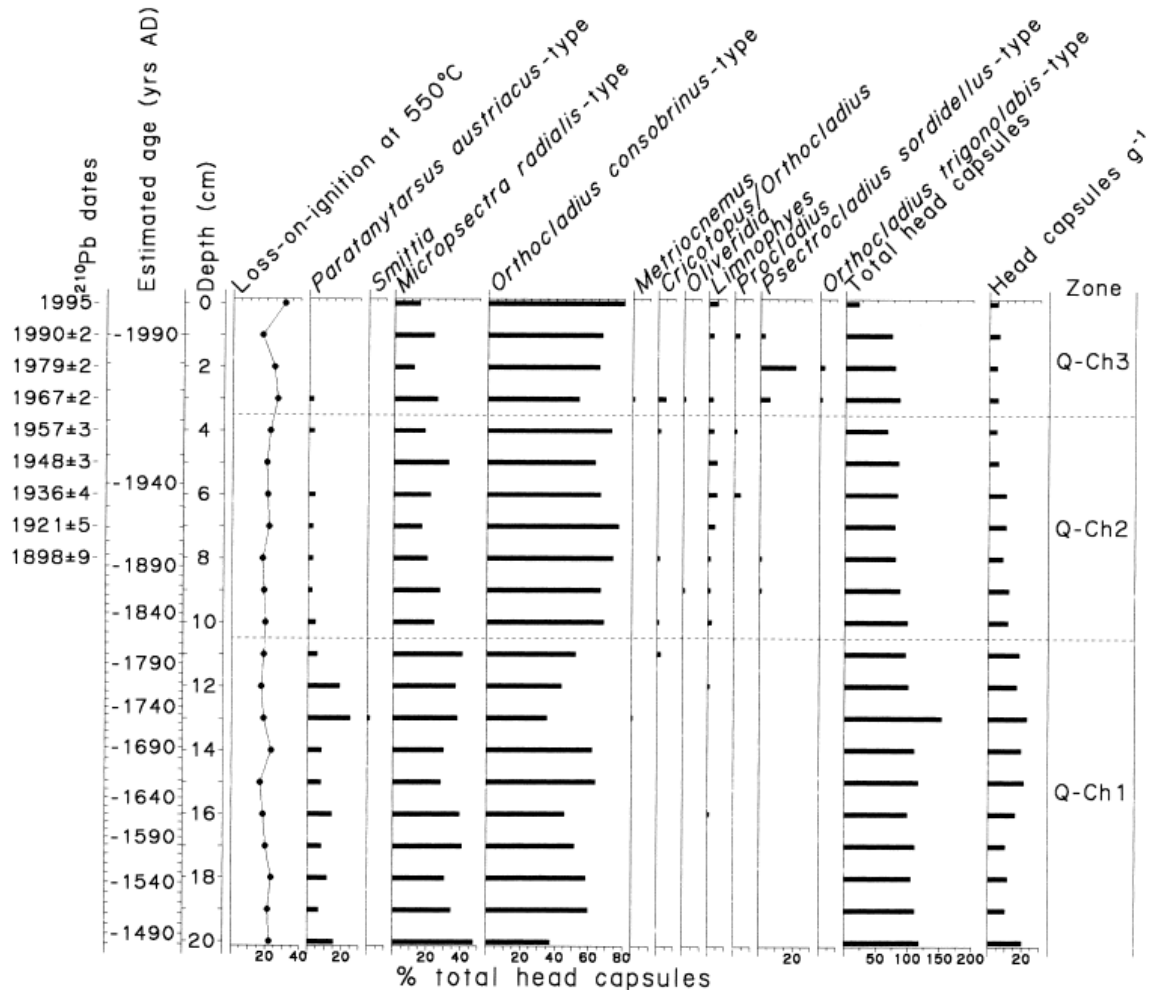

Figure 11. Changes in percentage abundance of Chironomidae in a 20 cm sediment core from Ytertjørna (Q), Spitsbergen.

Ecological interpretation. Unlike any of the other lakes in this study, *Limnophyes*, *Metriocnemus*, and *Smittia* are all abundant at Tenndammen (U) whereas both *Orthocladius consobrinus*-type and *Micropsectra radialis*-type are present in relatively low abundance. In the other lakes studied, one or other of these latter taxa dominate the chironomid fauna. The CA time-track and biplot (Figure 10c) show a complex pattern which shifts from productive, high pH conditions at the base of the core, to slightly less productive at 7.5 cm (1930 AD) and then back to more productive conditions at the top of the core. The major faunal change at 7.5 cm, where there is a decline in *Smittia* and a large increase in *Tanytarsus lugens*-type and *Orthocladius consobrinus*-type, is dated to about 1930 AD (Appleby 2004), soon after the known start of human activity adjacent to the lake. LOI values also increase slightly at this time. There is evidence of extensive former human activity at the lake, with the ruins of an old pump-house still there. From 1910 the lake

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was used to supply water to the settlement of Colesbukta, but the coalmine was closed in 1967 and the last people left the settlement in 1988.

The high abundance of *Tanytarsus lugens*-type around 6 - 7 cm (> 60% of the chironomid fauna) is unprecedented in any of the other lakes studied. This taxon may have been able to exploit new ecological opportunities following the start of human habitation around the lake. However, the success of this taxon was relatively short-lived and within 40 years the population had crashed again. It was replaced by *Orthocladius consobrinus*-type, which increased rapidly after the *Tanytarsus lugens*-type decline, and this suggests that *Tanytarsus lugens*-type may have been at a competitive disadvantage once *O. consobrinus*-type had become established in the lake. The reappearance of *Smittia, Metriocnemus, Chironomus anthracinus*-type, and *Paratanytarsus austriacus*-type at an abundance above 10% in the upper 1 cm of the core, after about 1990 AD, closely follows the end of human activity in 1988, and suggests that pre-human impact conditions were beginning to return. Although LOI values are at their highest in the 1990s, this may be a preservation effect since LOI is usually highest at the top of most cores (but see Boyle et al. 2004).

The low head capsule concentrations in this core are probably as a result of high sedimentation rates due to high lake productivity.
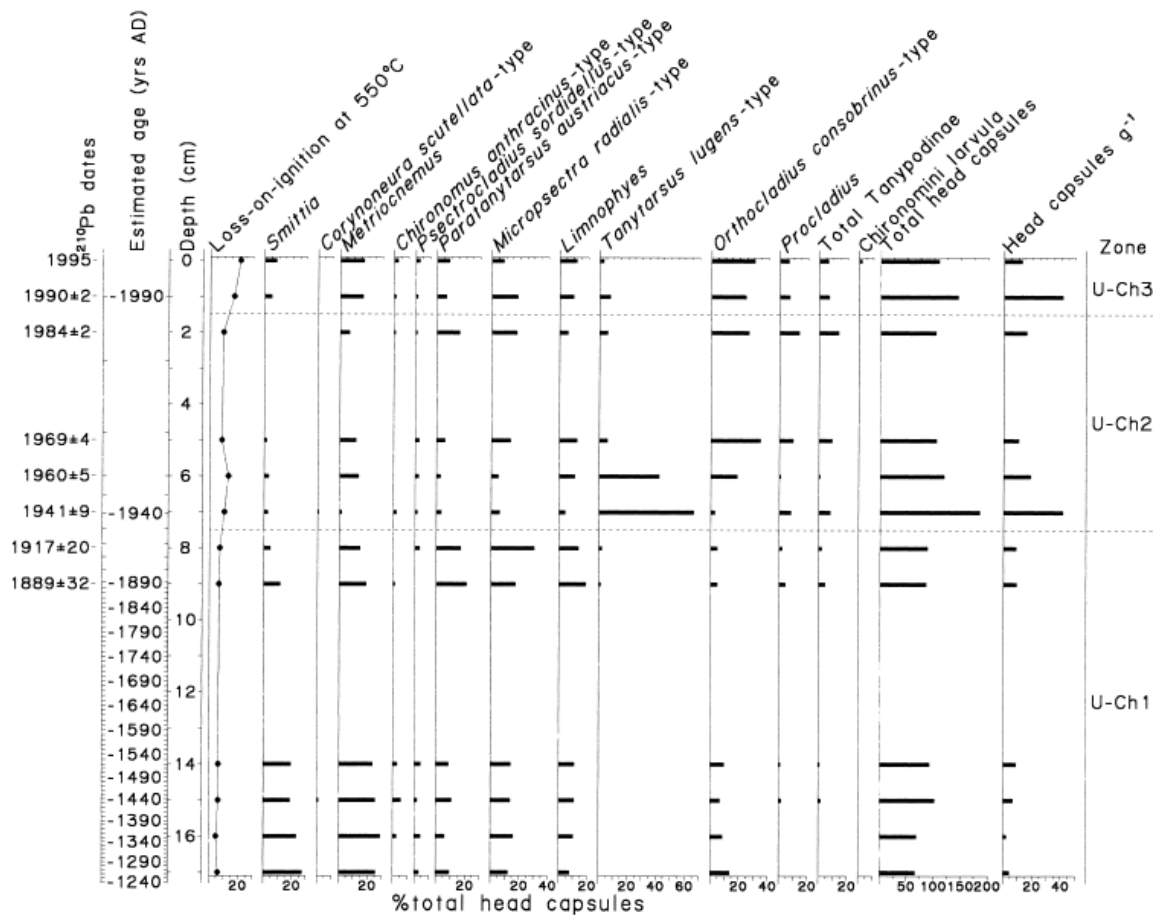

Figure 12. Changes in percentage abundance of Chironomidae in a 17 cm sediment core from Tenndammen (U), Spitsbergen.

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Ecological synthesis

The chironomid faunas of all three lakes show marked biotic changes in the last 200 - 300 years (Figure 10). At two of the lakes (Ossian Sarsfjellet (C) and Ytertjørna (Q)) major changes appear to have occurred at approximately the same time. The apparent synchronicity of the faunal change in lakes C and Q, at about 1830 AD, suggests some biotic response to a regional environmental change, possibly associated with a phase in the termination of the 'Little Ice Age' (LIA) (Grove 1988). However, a date of 1830 AD for the end of the LIA is somewhat earlier than dates suggested by other workers. For example, based mainly on changes in width of tree rings, Overpeck et al. (1997) suggest that temperatures in the Arctic began to rise from about 1840 AD and Werner (1993) noted that the LIA limit of the Midre Lovénbreen glacier on Spitsbergen was not reached until 1880 AD. Similarly, a date of 1880 AD is given for the termination of the LIA based on a variety of proxies (but not oxygen isotopes) in an ice core from northern Spitsbergen (Fujii et al. 1990). However, midges respond quickly to climate change and the midge assemblages in our Svalbard lakes may have responded more rapidly to climate change than these other climate proxies. The LIA is thought to have begun 500 - 600 years ago (Svendsen and Mangerud 1997; Snyder et al. 2000) when glaciers expanded more than at any other time during the Holocene. Our core at Ytertjørna (Q) does not extend far enough back in time to have a record of the beginning of the LIA but at Ossian Sarsfjellet (C) there is a sharp rise in *Orthocladius consobrinus*-type at about 1470 AD which may be a response to climatic change. However, although the core from Tenndammen (U) extends to before the presumed start of the LIA, and *Orthocladius consobrinus*-type is present in the assemblage, there is no change in the midge fauna of this lake at the time the LIA may have begun.

Although there appears to have been a synchronous change in the midge assemblages at lakes C and Q, suggesting some response to regional climate change, it is surprising that the nature of the faunistic changes is rather dissimilar at the two sites. In lake C, a decline in *Orthocladius consobrinus*-type and increases in *Orthocladius trigonolabis*-type and *Hydrobaenus conformis* during the last 200 years suggest a fall in the lake's trophic status. Conversely, in lake Q the rising abundance of *Orthocladius consobrinus*-type and decline in *Micropsectra radialis*-type suggest that this lake may have become more productive during the same period. The ecological mechanisms for these apparently paradoxical biotic responses to what presumably is the same regional climate change remain unclear. Lake Q is a coastal strandflat lake frequented by seabirds, which may have used the lake in the last 200 years as one of the few open freshwater bodies in the area, possibly leading to increases in nutrient input from bird guano. On the other hand, lake C is situated further inland and had glaciers in its catchment until about 1950 AD (Norsk Polarinstitutt, unpublished photographs) and glacial meltwater may have cooled the lake water, leading to a decline in lake productivity until recent times. It is not known when these glaciers in the catchment began to advance in the LIA. Geomorphological evidence suggests that they extended almost to the southern shore of the lake and have retreated rapidly in the last 50 years.

Unfortunately, at lake U (Tenndammen), this critical period of environmental change about 200 years ago coincides with samples in which there were too few chironomid larval head capsules for analysis, so it is not possible to say if there were any changes in the chironomid fauna at this site at this time. However, a major faunal change occurred about 70 years ago. This appears to be a response to local human-induced changes in land-use and lake utilisation rather than to regional environmental change since no response is detectable at this time in the other two study sites (2 cm at lake C, 6.5 cm at lake Q).

Despite the different faunistic changes at the sites studies, there are statistically significant increases in the rate of compositional change at all three sites in the last 50 - 100 years, and also

between 200 and 250 years ago at Ossian Sarsfjellet (Birks et al. 2004a), suggesting increased rates of compositional change at all sites in recent centuries, possibly in response to regional climatic change.

Conclusions

Analysis of the chironomid fauna in cores covering the last 700 years from three lakes on Svalbard reveals a response in two of the lakes to regional climatic change that occurred about 200 years ago, and which may mark the onset of the ending of the 'Little Ice Age'. In one of these lakes there is also a response to environmental change that occurred about 500 years ago and which may mark the beginning of the LIA. In the third lake this period was not sampled but the impact on the chironomid fauna of a human settlement in the lake catchment, beginning in 1930 AD and ending in 1988 AD, is apparent. These results emphasise the sensitivity of Chironomidae to low-amplitude climatic and environmental change and how even a small human impact can result in a significant response by lake ecosystems in Arctic regions.

Acknowledgements

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