Recent environmental change and atmospheric contamination on Svalbard as recorded in lake sediments – an introduction*

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Abstract

This paper outlines an interdisciplinary project on recent environmental change and atmospheric contamination on the high Arctic archipelago of Svalbard (76º30'N – 80º30'N). It describes the rationale and aims of the project and summarises the location, climate, geology, vegetation, and land-use of Svalbard.

Introduction

The Arctic constitutes a unique and important environment with a significant role in the dynamics and evolution of the earth system. High Arctic biota and environments have long been assumed to be relatively 'pristine' and 'stable' because of the absence of any intensive local human impact and of any significant atmospheric contamination. Arctic biotic assemblages are commonly thought to have changed little over the last few thousand years. However, Overpeck et al. (1997) have shown, using a range of proxy data sources (e.g., ice cores, tree rings) that the Arctic has undergone significant climatic changes during the recent past, with a marked warming since the mid-19th century. These changes appear to be unprecedented when put in the context of available climatic time-series for the last 400 years (Overpeck op. cit.). Additionally, environmental changes such as declines in the total area of winter-snow cover on land and of declining sea-ice cover throughout the Arctic Ocean, are now well documented. These progressive changes are occurring across the very region where General Circulation Models predict the earliest and largest greenhouse warming (IPCC 2001). Although inter-annual to century-scale climatic variation may be the norm in the Arctic (Overpeck op. cit.), there are very few historical biological, chemical, or palaeoecological data from the high Arctic, especially in Europe, to test for biotic responses to recent environmental change. The lack of such data is particularly critical as the Arctic is increasingly being recognised as an area that is potentially highly susceptible to global warming as well as being very sensitive to impacts from atmospheric pollutants.

Lake-sediment records from high Arctic lakes can provide unique data on recent biotic changes and pollution levels in remote areas where expensive long-term monitoring has not been possible. By analysing the fossil and chemical composition of lake sediments and by deriving an independent chronology for the sediments by means of ^{210}Pb-dating, it is possible to consider questions such as what is the rate and direction of recent change in lake biota and what is the timing and magnitude of atmospheric contamination? Additionally, the stability of Arctic biotic assemblages and their response to recent environmental change, and the extent of recent changes in lake trophic status and acidity, all of which can be influenced directly or indirectly by changes in climate and pollution, can be examined. High Arctic lakes may be among the most sensitive ecosystems to climatic change and to atmospheric pollution because although there may be high mid-summer productivity in some lakes, the brief growing-season ensures a low annual production compared to lakes further south. Chemical weathering rates influence, in part at least, the supply of nutrients to lakes and these rates can themselves be strongly influenced by climate (Smol et al. 1991).

With funding from the Norges forskningsråd (Norwegian Research Council), we began in 1995 a multi-disciplinary project on 'Lake sedimentary records of recent atmospheric pollution and environmental change on Spitsbergen'. This issue of Journal of Paleolimnology brings together the results of the various studies carried out as part of this project. These included simple basic surveys of a range of lakes and their catchments in western Svalbard, together with sampling of recent and surface sediments.

Our project had the following major aims: (1) to develop a modern diatom - water-chemistry calibration data-set for Svalbard lakes and to study chironomid, pollen, and chrysophyte cyst assemblages in surface-sediments on Svalbard; (2) to reconstruct changes in lake conditions over the last 500 - 700 years from fossil diatom, chrysophyte, and chironomid assemblages preserved in sediments from selected lakes; (3) to establish the extent and impact of local and long-range atmospheric pollution on Svalbard lakes by analysing spheroidal carbonaceous particles (SCP), persistent organic compounds, and heavy metals in lake sediments; and (4) to assess what biotic changes have occurred in the last 500 - 700 years and to consider if any of the responses result from climatic change or from atmospheric pollution.

The project design involved (1) the sampling of water and surface-sediments (top 0.25 cm for diatom, chrysophyte, pollen, and SCP analyses, and top 1 cm for chironomid analysis) and the recording of lake and catchment information from 21 lakes on a south-north transect along western Svalbard running from 77°33'N to 79°48'N; (2) the collection of sediment samples for the analysis of persistent organic compounds at five of these lakes (one in the far north, one in the south, one near Ny-Ålesund, and two near Longyearbyen where there are potential local pollution sources) and of short (20 - 25 cm) sediment cores for diatom, chironomid, SCP, and geochemical analyses and ^{210}Pb-dating at five lakes along the south-north transect; and (3) the collection of core ‘bottom’ samples (the basal 1 cm of cores, usually 20 - 25 cm sediment depth) from the same 21 lakes for chrysophyte analysis. In addition, surface sediments and sediment cores from three lakes in north-west Svalbard collected in 1993 by Jones and Cameron as part of the European Union funded AL:PE-2 project were ^{210}Pb-dated and analysed for diatoms, SCPs, and inorganic geochemistry. The surface sediments from these three lakes were also analysed for chironomid remains. Unfortunately because of poor preservation and/or low concentrations, not all the sediment samples contained countable remains of particular types of organisms, so full stratigraphical analyses of all groups were only possible at one site.

The aim of this introductory paper is to describe in general terms the modern environment and land-use of Svalbard and hence to provide a common background for the other more detailed papers in this issue. The second paper provides more detail on the lakes and their catchments. This is followed by six thematic papers dealing with dating, diatoms, chrysophytes, chironomids, SCPs, inorganic pollutants and persistent organic pollutants, and inorganic geochemistry. The final paper attempts to synthesize the evidence for recent biotic change and atmospheric contamination on Svalbard and assesses the possible factors that may have influenced the observed changes. The nine papers included in this issue are listed in the Appendix.

Svalbard – location, climate, geology, vegetation, and land-use

Location

Svalbard is the geographical name of the high Arctic archipelago situated between 76°30'N and 80°30'N and between 10°E and 35°E. It also includes the isolated island of Bjørnøya at 74°30'N. Svalbard is 657 km north of the most northerly point on the Norwegian mainland, halfway to the North Pole. It is the most northerly settled land in the world and even has its own University College (UNIS) at Longyearbyen. The name Svalbard is a modern version of the old Nordic name Svalbardr (Sval = cold, bardr = rim, edge, or border). It became the name for the whole archipelago when Norway was granted sovereignty in 1925 as part of the

Svalbard Treaty that gives equal rights for the Treaty nations to conduct industrial activity on Svalbard. The largest islands are Spitsbergen, Nordaustlandet, Edgeøya, Barentsøya, Prins Karls Forland (Figure 1), and, to the east, Kong Karls Land, Hopen, and Kvitøya. The archipelago covers nearly 63,000 km^2, about the size of Belgium and the Netherlands combined. Spitsbergen is the largest island, with an area of just over 39,000 km^2. Its name (meaning pointed mountains) was coined by the Dutch explorer Willem Barentsz in 1596, although Svalbard is mentioned in Icelandic annals from 1194 (Haartsen and Hacquebord, 1996). Hisdal (1985, 1998) and Umbreit (1997) give further details of Svalbard's geography and early discovery and settlement.

Figure 1. The Svalbard archipelago and (inset map) its position relative to the North Pole and mainland Norway. Islands, places, and fjords mentioned in the text are labelled.

Our project was confined to Spitsbergen and the nearby islands of Prins Karls Forland, Danskøya, and Amsterdamøya (Figure 1). Spitsbergen consists mainly of rugged steep mountains with spectacular alpine peaks rising to 1,717 m (Newtontoppen and Perrietoppen, both in north-eastern Spitsbergen). The western and northern coasts are deeply indented by steep-sided fjords, of which the two largest, Isfjorden on the west coast and Wijdefjorden on the north coast, nearly cut Spitsbergen into two. There is an extensive strandflat along much of the west coast, forming a rather level lowland area extending from the seashore to the lower slopes of the mountains at about 100 - 200 m. The strandflat varies from 100 - 500 m to 10 km in width and is the main area for most lakes and almost all plant and animal life on Spitsbergen. About 60% of the land area of Svalbard is covered by glaciers and the largest ice-free areas are in the central and western areas. Glaciers are particularly extensive in the north-east, and are up to 200 km long on Nordaustlandet. Along western Svalbard, an arm of the Gulf Stream, the so-called Norwegian Current, flows northwards to create the northernmost area of open water in the Arctic. Another arm of the Norwegian Current flows into the Barents Sea. These currents, coupled with much cyclonic activity, result in western Svalbard having a milder climate and a long period free of sea-ice than expected, given its northern situation. Its climate can thus be termed arctic-oceanic (Hisdal 1985, 1998). In contrast, eastern Svalbard is influenced by cold currents from the north.

Climate

The mean temperature of the three coldest months (January, February, and March) is -11.9°C at Isfjord Radio (78°4'N, 13°28'E) in the outer-fjord area (Figure 1). This is high compared to, for example, Mys Chelyuskin (77°40'N, 104°E) at the northernmost point on the Eurasian continent but at the same latitude as Svalbard, where the corresponding mean temperature is -26°C. Summers are also relatively mild on Svalbard with a mean July temperature of 4.7°C at Isfjord Radio and 6.5°C at Longyearbyen (Figure 1). The growing season is only about six to eight weeks. The mean annual temperature at Isfjord Radio is -4.7°C and at Ny-Ålesund (78°56'N, 10°53'E) -5.8°C, some 6 - 7°C warmer than at corresponding latitudes in eastern Greenland (Hisdal 1985, 1998; Umbreit 1997).

Mean annual precipitation is about 400 mm along the west coast, decreasing to 200 - 300 mm towards the heads of the fjords and the main inland areas (Steffensen 1982). Precipitation is higher than at other Arctic areas of comparable latitude. Although 200 mm is similar to the annual precipitation in semi-desert areas, on Svalbard much of the precipitation falls as snow and the low temperatures result in low evaporation. Much of western Svalbard is snow-covered between early September and late May or early June. The widespread occurrence of permafrost, extending from less than 100 m depth near sea-level to over 450 m depth at altitudes of 500 m above sea-level in the interior (Liestøl 1975; Hjelle 1993), keeps water at or near the soil surface for much of the growing season. During summer, the uppermost ‘active’ layer may thaw to a depth between 30 and 150 cm. In Longyearbyen, the Midnight Sun is visible from 21 April to 21 August, giving 122 days of continuous daylight, increasing to 141 days at 81°N. Advective fog drizzle, formed when mild, humid air moves slowly over ice or a cold ocean surface, is common in the summer, and both snow and rain can occur in every month of the year. The hours of bright sunshine are few. Winds are predominantly north-easterly in winter and southerly or westerly in summer. Further details of the climate of Svalbard are given by Steffensen (1982) and Hanssen-Bauer et al. (1990).

Based on homogenised meteorological observations from 1912 to the present, Førland et al. (1997) document an increase in annual temperature on Spitsbergen from 1912 to the late 1930s, a decrease in annual temperature in the 1930s to 1960s, and an increase in annual temperature from the 1960s to the present. Changes in winter temperature dominate the changes in annual temperature up to the 1960s, whereas changes in spring temperature dominate the increase since the 1960s. Spring is the only season that shows a statistically significant warming from 1912 to 1996 (Hanssen-Bauer and Førland 1998). In contrast to the rest of northern Europe and the Northern Hemisphere as a whole, the current annual temperature on Spitsbergen is lower than it was in the 1930s but is about the same as it was in the 1920s. The warming before the 1930s was considerably more dramatic on Spitsbergen than in the Northern Hemisphere as a whole. Annual precipitation has increased on Spitsbergen by about 25% since 1912, more than on the Norwegian mainland or the 'average high latitude increase' (Førland et al. op. cit.). Hanssen-Bauer and Førland (1998) show by statistical modelling that the decadal scale variability and trends in precipitation are closely correlated to variation in atmospheric circulation patterns associated with the North Atlantic Oscillation, possibly influenced by an enhanced 'greenhouse effect'. The increase in annual mean temperature since the 1960s is well explained statistically by changes in advection, but the temperature increase from the beginning of the measurement to the 1930s and the temperature decrease from the 1930s to the 1960s are poorly explained in terms of circulation patterns. Additional factors such as sea-ice, sea-surface temperatures, and cloudiness may have been important in influencing the temperature trends in the early part of the last century.

Most glaciers on Spitsbergen advanced during the 'Little Ice Age' to form extensive and well-preserved moraines and reached their maximum Holocene position during the 19th century (Svendsen and Mangerud 1992). The glaciers retreated with subsequent 20th century warming (Werner 1993) with temperatures warmer than at any other time in the last 500 years (Tarussov 1992). There is evidence for recent glacial retreat, especially in the inner-fjord areas, since about 1950 - 1960 (e.g., Ziaja 2001, 2002; Hagen and Liestøl 1990; Werner 1993; cf. Humlum 2002). Ice-core data from Svalbard suggest a duration of the 'Little Ice Age' from 1550 - 1920 AD (Tarussov 1992). Other ice-core records suggest a two-phase development with cold periods between 1200 - 1500 AD and 1700 - 1900 AD (Gordiyenko cited in Svendsen and Mangerud 1997).

The cooler, damper climate of the outer west coast, with frequent coastal fogs, greater precipitation, and reduced radiation, contrasts with the warmer, sunnier, and drier climate of the inner-fjord areas. This climatic gradient is reflected by the absence of the white arctic bell-heather *Cassiope tetragona* in the outer coastal areas and by its local luxuriance in the inner-fjord areas. The amount of vegetation cover generally increases as one moves from the coast to the inner-fjord areas (Elvebakk 1997; Birks 2001). The general vegetation patterns at the landscape-scale are vegetation-covered valley floors in the inner-fjord areas, more or less barren slopes in the outer coastal areas, and barren mountain plateaux (Elvebakk op. cit.). The coldest areas in the east and north-east have almost no vegetation cover, even at sea level and are polar deserts (Elvebakk op. cit.).

Geology

Geologically Svalbard is extremely varied (Hjelle 1993; Elvebakk 1997). All geological systems from the Pre-Cambrian to the Quaternary are well represented. In the areas of western Svalbard where our project was based, gneiss and schist of Pre-Cambrian to lower Palaeozoic age predominate, with some granite, Carboniferous and Permian limestone, Devonian sandstone, and Tertiary volcanic and sedimentary rocks.

Almost all the western coast and the area east of Wijdefjorden consist of basement schistose and gneissic rocks. A few small areas in the north-west (Danskøya and Amsterdamøya) and in Nordaustlandet consist of granite. Dolerite occurs scattered through most of Svalbard but is most frequent in the east. Basic intrusions occur in the north-east.

Remains of Tertiary and Quaternary volcanoes form some mountain peaks in northern central Spitsbergen and north-east of Ny-Ålesund. The largest parts of Svalbard consist of sedimentary rocks that are weakly acid but a large Carboniferous/Permian limestone area runs across Svalbard from the Ny-Ålesund area to Nordaustlandet. Red Devonian sandstone forms large areas of central northern Spitsbergen and this is mostly calcareous (Elvebakk op. cit.). Further details of the geology of Svalbard are given by Hjelle (op. cit.).

Vegetation

The vascular plant flora of Svalbard includes 168 native species and a few introduced species (Elvebakk 1997; Elven and Elvebakk 1996; Rønning 1996). In addition, at least 373 species of bryophyte, 606 lichen species, 705 fungi, and just over 1,100 terrestrial, freshwater, and marine algae and Cyanobacteria are recorded (Elvebakk and Prestrud 1996).

The vegetation of western Svalbard largely lies within the northern arctic-tundra and arctic polar-desert zones with some middle arctic-tundra vegetation in the inner-fjord areas (Elvebakk op. cit.). There is a sparse, low-growing cover in much of the outer-fjord areas of *Salix polaris, Cerastium arcticum, Saxifraga cernua, S. cespitosa, S. oppositifolia, S. hirculus, Luzula arcuata, L. arctica,* and *Poa arctica*, typical of the northern arctic-tundra zone (Birks 2001; Elvebakk op. cit.; Moen 1999). The very open arctic polar-desert of the extreme north and areas at an elevation above about 100 m lack *Salix polaris* but *Papaver dahlianum* is locally frequent along with *Poa arctica, Phippsia algida, Luzula* spp., *Cerastium arcticum, C. regelii, Saxifraga* spp., and *Sagina nivalis* and a range of bryophytes and lichens. In the inner-fjord areas the vegetation belongs to the middle arctic-tundra zone with locally frequent *Dryas octopetala*, *Cassiope tetragona, Salix reticulata, S. polaris, Saxifraga oppositifolia, S. hirculus*, and *S. nivalis* and extensive moss-dominated carpets (Elvebakk op. cit.; Moen 1999; Birks 2001). The arctic polar-desert zone includes areas with mean temperatures of the warmest month of 3ºC or less, whereas the northern arctic-tundra zone occurs within the range 3 - 5ºC and the middle arctic-tundra zone occurs in the range 5 - 7ºC (Elvebakk op. cit.).

Plant macrofossils from a Holocene lake sequence situated today in the northern arctic-tundra vegetational zone of the outer-fjord area of western Spitsbergen indicate that vegetational cover was considerably denser there in the past and resembled middle arctic-tundra vegetation of modern inner-fjord areas from about 8,000 to 4,000 years ago. The fossil assemblage suggests that summer temperatures may have been about 2ºC warmer than today in the early- and mid-Holocene. The vegetational cover became more open and began to resemble northern arctic vegetation by about 2,500 years ago, presumably in response to late-Holocene climatic cooling (Birks 1991).

Land-use

After the discovery of Spitsbergen in 1596, hunting of walrus, whale, and seal began in the early part of the 17th century by the English trading Muscovy Company and soon afterwards by the Dutch Noordse Compagnie. Dutch whaling stations were built in north-western Svalbard in about 1620 and were occupied until about 1660 (van der Knaap 1985; Haartsen and Hacquebord 1996; Hisdal 1998). At the peak of hunting activity in the 1630s, about 200 people lived on Svalbard in the summer. In the early 18th century, Russia built year-round habitations and in addition to walrus, seal, and whale, reindeer, fox, and polar bear were hunted. By the end of the 18th century, Russian hunting activities were at their peak and about 150 people manned the hunting stations. Whaling continued through the 18th century but the yield fluctuated greatly, possibly in response to climate (Haartsen and Hacquebord 1996). By the beginning of the 19th century, so few whales remained that the whaling industry ceased to be economic. In the middle of the 19th century, Russian hunting and trapping stopped abruptly (Hisdal 1998). Norwegian hunting of walrus, polar bear, and fox had begun in the 1790s and expanded in the 19th century. Habitations and human impact were very localised with small huts scattered around most of the archipelago. The walrus population was so decimated by the mid 19th century that almost all walrus hunting became uneconomical and was disbanded.

In the 20th century, the major exploitation of Svalbard was coal mining, primarily by Norway and Russia. The main Norwegian mining areas were in western Svalbard; in or near Longyearbyen, at Ny-Ålesund, and at Sveagruva at the head of Van Mijenfjorden. The Russian mines were centred at Barentsburg, Grumantbyen, and Pyramiden. Today, at Longyearbyen, there is only one operative mine and most coal production is concentrated at Sveagruva. The coal is used for local power production in Longyearbyen but coal was also used in the power stations at Barentsburg and Pyramiden in western Isfjorden for at least 40 years (Rose et al. 2004).

Today, about 1,600 Scandinavians live all year on Svalbard, mainly in Longyearbyen, Ny-Ålesund, and Sveagruva working in tourism, administration, the University College, and research institutes. About 600 Russians lived all year in Barentsburg and about 600 in Pyramiden until mining ceased in 1998. The Russian population has declined considerably since 1998.

Compared to other Arctic areas, the native Svalbard herbivorous fauna is very impoverished with an endemic subspecies of reindeer (*Rangifer tarandus* ssp. *platyrhyrichus*), no musk ox or native hares, the Svalbard ptarmigan (*Lagopus mutus* ssp. *hyperboreus*), and the migratory barnacle goose (*Branta leucopsis*), brent goose (*B. bernicola*), and pink-footed goose (*Anser brachyrhynchus*) (Elvebakk 1997). There are few terrestrial predators on Svalbard compared to other Arctic areas with only the arctic fox (*Alopex lagopus*), the glaucous gull (*Larus hyperboreus*), the great black-backed gull (*L. marinus*), and the great skua (*Stercorarius skua*). Wolves, owls, falcons, and ravens are all absent (Elvebakk op. cit.).

Conclusions

Svalbard is a unique area in Europe for palaeolimnological studies for a number of reasons: (1) its high latitude, (2) its arctic-oceanic climate; (3) its wide range of lakes; (4) its limited flora and fauna are relatively well known; (5) it has received little or no human impact since its discovery in 1596; (6) it is far removed from major sources of atmospheric pollution but some long-range transport of pollutants has been reported; (7) local atmospheric pollution sources are very restricted; (8) it has experienced recent climatic changes, with marked changes in mean annual temperature, precipitation, and spring and winter temperatures since records began in 1912; and (9) it is one of the most easily accessible parts of the high Arctic.

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Appendix

Papers in the Svalbard issue of Journal of Paleolimnology.

Birks H.J.B., Jones V.J. and Rose N.L. Recent environmental change and atmospheric contamination on Svalbard as recorded in lake sediments – an introduction.

Birks, H.J.B., Monteith, D.T., Rose N.L., Jones V.J. and Peglar S.M. Recent environmental change and atmospheric contamination on Svalbard as recorded in lake sediments – modern limnology, vegetation, and pollen deposition.

Appleby P.G. Environmental change and atmospheric contamination on Svalbard: sediment chronology.

Jones V.J. and Birks H.J.B. Lake-sediment records of recent environmental change on Svalbard: results of diatom analysis.

Betts-Piper A.M., Zeeb B.A. and Smol J.P. Distribution and autecology of chrysophyte cysts from high Arctic Svalbard lakes: preliminary evidence of recent environmental change.

Brooks S.J. and Birks H.J.B. The dynamics of Chironomidae (Insecta: Diptera) assemblages in response to environmental change during the past 700 years on Svalbard.

Rose N.L., Rose C.L., Boyle J.F. and Appleby P.G. Lake-sediment evidence for local and remote sources of atmospherically deposited pollutants on Svalbard.

Boyle J.F., Rose N.L., Appleby P.G. and Birks H.J.B. Recent environmental change and human impact in Svalbard: the lake-sediment geochemical record.

Birks H.J.B., Jones V.J. and Rose N.L. Recent environmental change and atmospheric contamination on Svalbard as recorded in lake sediments – synthesis and general conclusions.