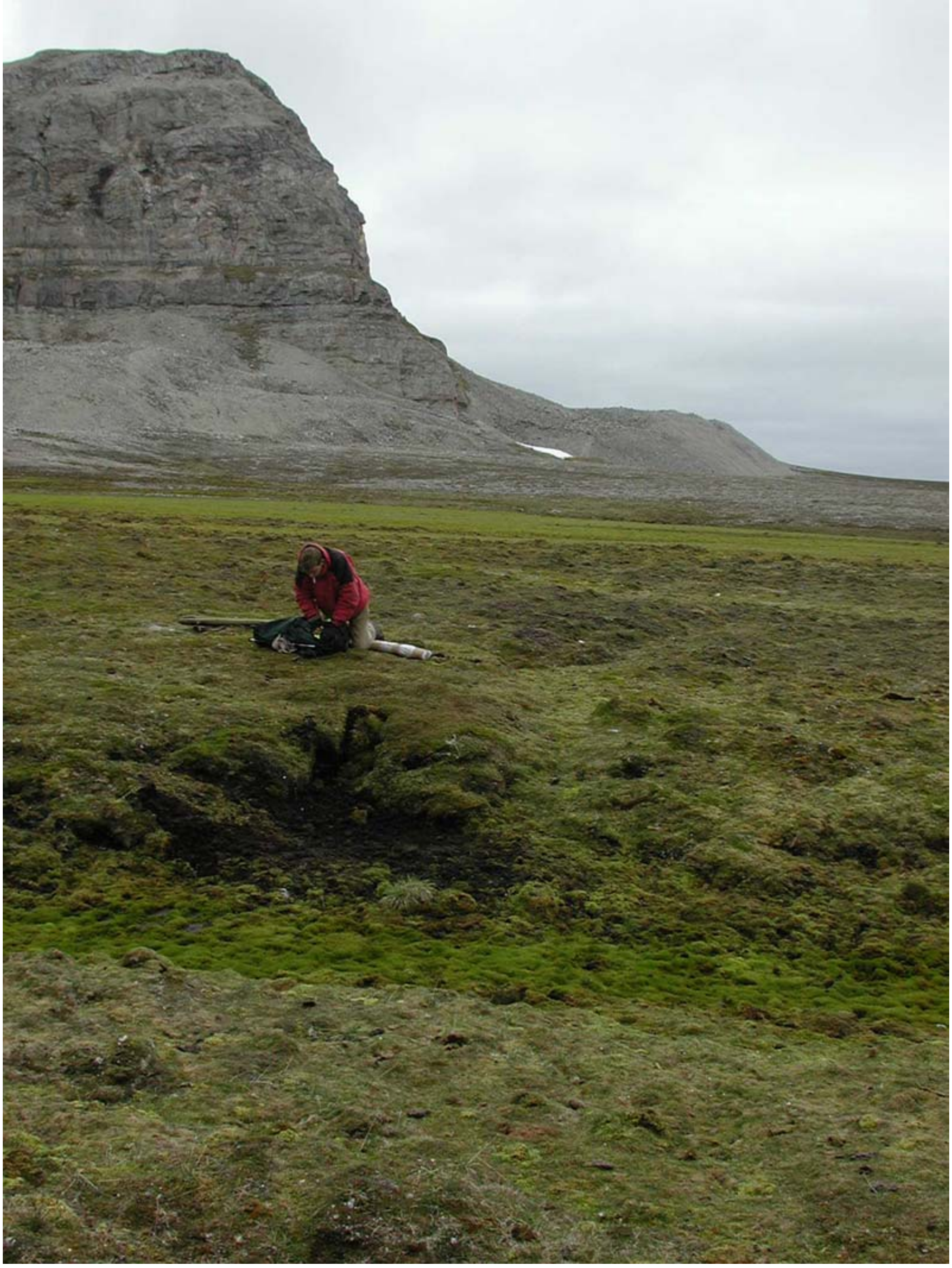

Photo. Arctic tundra peat in front of Stuphallet, Brøggerhalvøya, not far from Ny Alesund.Nutrient enrichment by nesting seabirds at the steep rocks of Stuphallet stimulates growth of many arctic plants. Because of the permafrost at 15–20 cm below ground level, and soil melt-water in the summer period, the wet tundra soil is waterlogged. A peat profile was sampled with a depth of 105 cm using a motor-driven soil corer with a saw-tooth end. Photograph by J. Rozema.

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A vegetation, climate and environment reconstruction based on palynological analyses of high arctic tundra peat cores (5000–6000 years BP) from Svalbard

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Abstract

As a reference for ongoing studies reconstructing past vegetation, climate and environment, pollen spectra in tundra peat profiles from Svalbard, were investigated. The base of tundra peat cores collected from Ny Ålesund, Stuphallet, Blomstrand and Isdammen has been ^{14}C dated to 350–490 BP, 5710 BP, 4670 BP and 700–900 BP, respectively. The Stuphallet and Blomstrand (Brøggerhalvøya) peat profiles were composed of a peat developed in a nutrient enriched and wet tundra environment of steep birdcliffs. Pollen concentrations were low, *Brassicaceae* pollen dominated the whole profile. In contrast, the Ny Ålesund and Isdammen profiles contained high pollen concentrations and suggest a nutrient-poor, dry tundra environment. Pollen of the polar willow, *Salix polaris*, occurred commonly throughout all four peat profiles. In the relatively high resolution (10 years per peat core sample) analysis of the Ny Ålesund core, starting before or at the beginning of the Little Ice Age (LIA, 16th-mid 19th century), dominance of *Saxifraga oppositifolia* indicates a cold and dry climate, followed by a decline of *Saxifraga oppositifolia* and gradual increase of *Salix polaris* after the LIA, which indicates a moist and milder climate.

Introduction

The research presented here forms part of a project aimed at assessing and analysing the interactions between climate change and the plant species of arctic terrestrial ecosystems. This approach includes field experimental study of the response of terrestrial plant species to global warming with Open Top Chambers (e.g. Aerts et al. 2005; Blokker et al. in prep.; Rozema et al. in prep.), and to enhanced UV-B as a result of changes of stratospheric ozone concentrations (Boelen et al. 2005; Blokker et al. 2005; Rozema et al. 2005). Antarctic and arctic terrestrial ecosystems are pre-eminently suitable to this research purpose since both global warming and ozone depletion are most pronounced in polar regions (Farman et al. 1985; Mc Peters et al. 1996; Newman et al. 1997; Hassol, ACIA 2004).

While the average global warming is estimated broadly at 2.5 °C for the period 2000–2100 (IPCC 2001) winter temperatures in arctic areas (60–90° North) tended to increase by 2–4 °C during the past 50 years (Hassol 2004) and the projected increase of arctic winter temperature is 4–7 °C for 2000–2100 (IPCC 2001).

In addition to various abiotic proxies (e.g. isotope ratio's $^{18}O/^{16}O$, Isaaksson et al. 2003; periglacial features, Isarin 1997), reconstruction of past temperature and UV regimes can be based on palynological analyses and plant-climate indicator relationships (Iversen 1954; Zagwijn 1994; Isarin 1997; Isarin and Bohncke 1999), extended with experimentally obtained plant temperature and plant UV-B dose response or transfer relationships. The latter comprises climate induced chemical changes in plants, e.g. flavonoids, para-coumaric acid and ferulic acid in pollen and macrofossil plant remains (Blokker et al. 2005).

The Spitsbergen archipelago (74–84° N, 10–35° W) forms part of the Arctic, far north of the polar circle. Owing to the warm Gulfstream water along the west coast of Spitsbergen, the climate is less extreme than at more northern and eastern parts of Svalbard. The mean annual temperature for 1975–1996 for Longyearbyen was −5 °C and the mean July temperature for this 22 year period was +6.6 °C (Hisdal 1985, 1998; Rønning 1965, 1996). Overall on Svalbard, average winter temperature varies from −15 to −20 °C and mean summer temperature from +5 to +8 °C.

Precipitation is 400 mm per year in the west, where a major part falls as rain or moist fog, and 200–300 mm further inland (Steffensen 1982). The vegetative summer period is relatively short, i.e. between 40 and 70 days. Vegetation-climate regions have been recognized consisting of (a) a barren zone, (b) the White arctic bell-heather zone, (c) the Mountain Avens zone and (d) the inner fjord zone, corresponding to some extent with dominance of *Cassiope tetragona* (b), *Dryas octopetala* (c) and *Salix polaris* (d) (Elvebakk 1994, 1997; Rønning 1996). Vegetation at the foot of steep cliffs used by nesting birds, enriched with droppings (guano) is characterized by *Brassicaceae*, *Polygonaceae* and (some) grass species. According to Elvebakk (1997), the mean temperature of the warmest month (MTWM) of polar deserts with *Saxifraga oppositifolia* is 3 °C , the MTWM of the northern arctic tundra with *Salix polaris* is 3–5 °C and the MTWM of the middle arctic-tundra zone (inner fjord area) with *Cassiope tetragona* and *Dryas octopetala* is 5–7 °C.

Based on this and the literature, vegetation, environment and climate relationships are used and described in Table 1. This data set has subsequently been used to infer climate and environmental changes from the pollen diagrams.

More generally, the practice of inferring past climate change with Climate Indicator Species has been described by Zagwijn (1994), Isarin (1997), Isarin and Bohncke (1999). For this purpose, the relationship between plant parameters and the mean annual air temperature (MAAT) is used, or the minimum (or maximum) mean temperature of the warmest (or coldest) month. Often these climate parameters represent threshold values, i.e.

Table 1. Climate indicator species used for climate–plant relationships on Svalbard used for reconstruction of climate and environmental changes inferred from the pollen diagrams.

Species	Indication	Reference
Caryophyllaceae: *Silene acaulis*, *S. uralensis*, *Cerastium*	Cold	Elvebakk 1985, 1997; Rønning 1965, 1996
Brassicaceae Cruciferae (Draba, Cardamine, Cochlearia, Braya)	Nutrient rich	v/d Knaap 1988a
Polygonaceae: (Oxyria, Bistorta)	Nutrient rich	Elvebakk 1985, 1997; Rønning 1965, 1996
Ranunculaceae	Wet, moist	Elvebakk 1985, 1997; Rønning, 1965, 1996
Cassiope tetragona	Warm, dry, nutrient poor	Elvebakk 1985, 1997
Poaceae: (Gramineae)	Nutrient rich	v/d Knaap 1988a, b
Salix polaris	Mild, wet	v/d Knaap 1989a
Saxifraga oppositifolia	Cold, dry, nutrient poor	v/d Knaap 1985, 1988a, b; Birks 1991, 1996; Aiken et al. 1999
Saxifraga stellaris	Wet and cold	Elvebakk 1985, 1997; Rønning 1965, 1996
Rosaceae (Dryas octopetala)	Dry, calcareous	Elvebakk 1985, 1997; Rønning, 1965, 1996

temperatures below which plants die, or above which plants flower and reproduce (Iversen 1954). It should be noted that no such quantitative transfer functions are available for high arctic tundra plants. Therefore the climate and environmental changes at the sites in this study can only be described qualitatively. Moreover, the climate and environmental factor relationships used here may be correlated and compound (e.g. cold and moist), obstructing reconstruction of single climate parameters such as temperature.

Antarctic moss peat banks at Signy Island, comparable in origin and age to the Svalbard peat cores of this paper, did not contain substantial pollen concentrations (Boelen et al. 2005). The Antarctic moss peat banks mainly consist of remains of mosses and their spores. This absence of pollen is not remarkable since only two flowering plant species occur in antarctic terrestrial environments. In addition, terrestrial Antarctic vegetation is often sparse and patchy. In contrast, the arctic flora of Svalbard includes 173 vascular plant species and high arctic tundra vegetation covers large areas on Svalbard (Barkman 1987; Summerhayes and Elton 1923; Elvebakk 1994; Elven and Elvebakk 1996; Elvebakk and Prestud 1996; Rønning 1996). Arctic peat cores may therefore contain more pollen than Antarctic peat deposits.

Peat formation in polar regions is much slower than at lower latitudes, since tundra plant growth is limited to a short and cold arctic summer. However melt and rainwater in the soil above the omnipresent permafrost layer at the depth of 10–100 cm (Rønning 1996) helps to preserve dead plant material. Once dead plant material has left the active layer and forms part of the permafrost, microbial and chemical decay is very slow or absent, and preservation of organic plant matter including pollen and spores is optimal.

The aim of this paper is (1) to reconstruct the past vegetation of Svalbard during the last few thousands of years by palynological analyses of peat cores and (2) to compare these pollen records with climate and environment indicator species and their present-day plant climate and environment relationships to reconstruct past climatic and environmental conditions of the arctic tundra.

Dependent on the age of the peat cores more detailed research aims are to describe vegetational and climatical changes during periods of marked or abrupt climatic change such as the Little Ice Age, as derived from earlier palynolological and abiotic proxy reconstructions (e.g. $^{18}O/^{16}O$ Isaakson et al. 2003).

Materials and methods

Core sampling sites and soil core description

Limited information is available on peat formation in the high arctic and locations on Svalbard and palynological analysis of terrestrial pollen deposits (cf van der Knaap 1985, 1987, 1988a, b; 1989a, b; 1991). The Ny Ålesund and Blomstrand cores were collected after reconnaissance trips around Kongsfjorden and based on van de Knaap (1988a) (Figures 1a, b and 4a–c). The Isfjorden peat core site near Longyearbyen was chosen in the vicinity of a UV-B supplementation field experiment and ITEX open top roofs, where present day pollen and vegetation analyses have been conducted (Rozema et al. 2005)

Ny Ålesund

In August 2000 a core was collected near Ny Ålesund (78° N, 11° E) (Figures 2, 4b). The average temperature for Ny Ålesund in February, the coldest month, is c. −15.0 °C. In July, which commonly is the warmest month, the average temperature is c. + 5.0 °C. The core (Figures 2, 4, 6) taken with a stainless steel corer, had a diameter of 40 mm and was 9.7 cm deep. The lithology is as follows: 0–3.8 cm: fresh moss peat, 3.8–6.0 cm: strongly humified peat, 6.0–9.7 cm: silt.

Peat material for ^{14}C dating was taken at 5.8–5.7 cm below the top of the core and was dated 280 ± 45 BP, indicating an age of 490 BP (1460 AD), (BP Before Present is standardized at AD 1950) , for the lower part (9.7 cm) of the core. The core was collected on a sun exposed dry arctic heather site dominated by *Cassiope tetragona* with a *Salix polaris* understorey (Figure 4b).

The composition of the present-day vegetation is: *Cassiope tetragona* (10–15%), *Salix polaris* (5–10%), the moss *Sanionia uncinata* (10–20%), *Oxyria digina*, *Bistorta vivipara*, *Saxifraga oppositifolia*, *S. cernua*, *S. hieracifolia*, *S. hirculus*, *Silene acaulis*, *Dryas octopetala*, *Cerastium arcticum*, *Alopecuris borealis*, *Poa alpina*, *Carex misandra*, *Luzula confusa*, *Stereocaulon alpinum* and white crustose lichens.

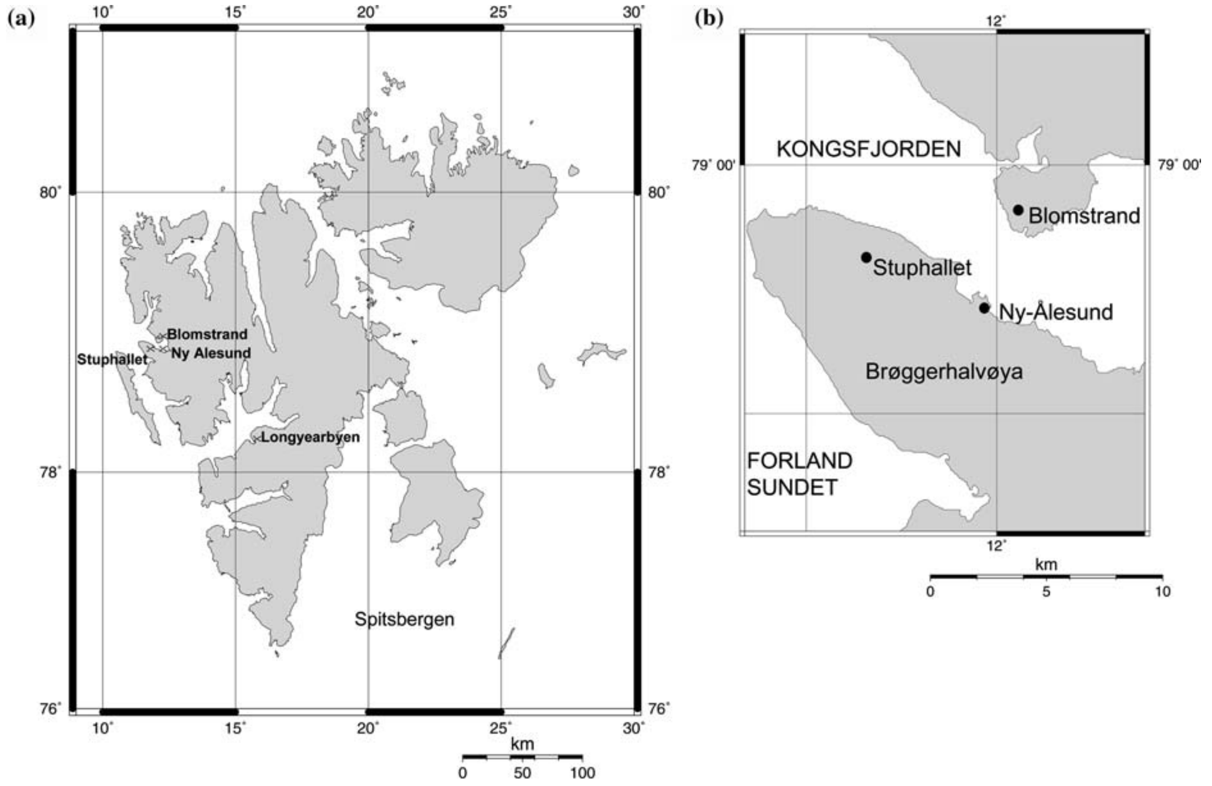

Figure 1. (a) Map of the Svalbard archipelago with the location of the peat core sites. 1. Stuphallet, 2. Blomstrand, 3. Ny Ålesund, 4. Isdammen. Peat cores 1 and 2 were collected on July 2002; peat cores 3 and 4 on August 2000. (b) Location of the peat core sites on Brøggerhalvøya, in the neighourhood of Ny Ålesund.Stuphallet and Blomstrand are peat areas adjacent to steep birdcliffs.

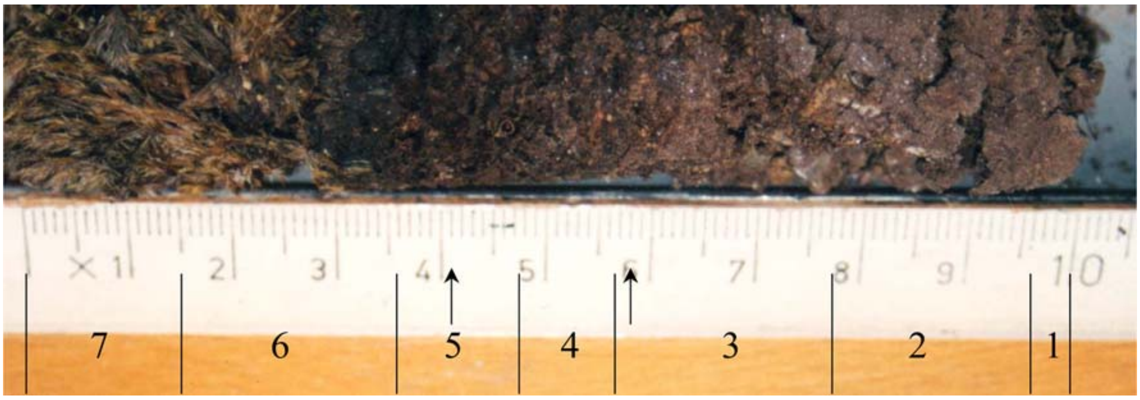

Figure 2. The Ny Ålesund peat core 9.7 cm long, collected on August 2000. The arrows indicate sampling for ^{14}C dating.

Blomstrand

In July 2002, a core was collected at the edge of a peat area in front of the bird cliffs at Blomstrand on Blomstrandøya (Figures 1, 7), which is a sun-exposed location, with the permafrost layer deeper than 70 cm at the edge of the peat area. The whole core was collected intact using a spade and a long knife. The peat core (Figure 3) was 67.4 cm

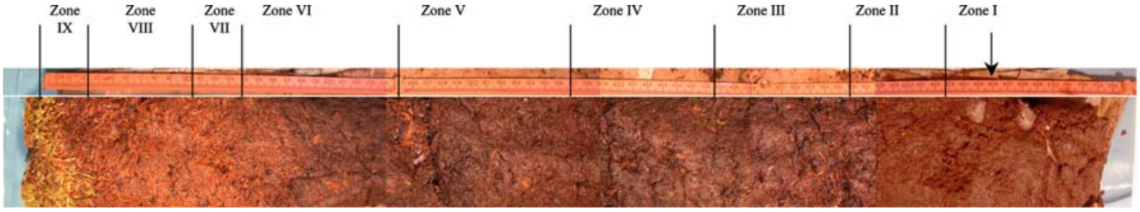

Figure 3. The Blomstrand peat core, 67.4 cm long, sampled July 2002.

deep. The lithology is as follows: Top layer 0–6 cm: living mosses, well preserved, yellow, 6–22 cm: moderately decomposed, dark brown, 22–32 cm: well preserved, dark brown, 32–62 cm: well decomposed, dark brown, 62–67.4 cm: moderately well preserved, dark/light brown. The core length was 67.4 cm with a diameter of 10 cm. Peat material for ^{14}C dating was taken at 65.2–67.4 cm depth, without reaching the permafrost layer. The composition of the present-day vegetation is: *Alopecurus borealis*, *Bistorta vivipara*, *Cassiope tetragona*, *Cerastium arcticum*, *Dryas octopetala*, *Oxyria digyna*, *Carex misandra*, *Luzula confusa*, *Draba* species, *Cochlearia groenlandica*, *Ranunculus hyperboreus*, *Salix polaris*, *Saxifraga cernua*, *Saxifraga hieracifolia*, *Saxifraga hirculus*, *Saxifraga oppositifolia*, *Silene acaulis*, *Stereocaulon alpestre* (lichen), *Sanionia uncinata*, *Polytrichum hyperboreum* (mosses), *Huperzia selago* (club moss).

Stuphallet

The permafrost layer was at 15–20 cm below ground level. In July 2002, samples were taken from the frozen peat using a motor-driven soil corer with a saw-tooth end with a diameter of 30 mm. The depth of the profile was 105 cm. Eighty sub samples, about 1.3 cm thick, were cut from the peat core. Forty subsamples were analysed at even intervals. Peat material for ^{14}C dating was taken at 103.7–105 cm depth. The species composition of the present-day vegetation is: the moss *Calliergon* spec. (20%), *Salix polaris* (5–15%), *Equisetum arvense* (horsetail), *Draba alpina*, *Draba* spec, *Braya purpurascens*, *Oxyria digina*, *Bistorta vivipara* (= *Polygonum viviparum*), *Dryas octopetala*, *Cerastium arcticum*, *Ranunculus pygmaeus*, *R. hyperboreus*, *Saxifraga hirculus*, *S. oppositifolia*, *S. cernua*, *S. hieracifolia*, *Sanionia uncinata* (5–10%), *Cardamine nymanii*, *Cochlearia groenlandica*, *Alopecurus borealis*, *Poa alpina*.

Isdammen

In August 2000, a core was collected near Longyearbyen, next to the drinking water reservoir Isdammen. The vegetation is dry and dominated by *Cassiope tetragona* and *Salix polaris*. The core was drilled with a stainless steel soil corer. The permafrost layer was not reached. Bedrock did not allow further coring. The core had a diameter of 3 cm and was 19 cm long. The lithology is at follows: 0–3.2 cm: humified peat with plant remains, 3.2–19 cm: humified peat. The species composition of the present-day vegetation, with percentage cover, is: *Salix polaris* (20–30%), *Cassiope tetragona* (40–50%), *Dryas octopetala* (5–10%), *Sanionia uncinata* (10–20%), *Polytrichum hyperboreum*, *Oxyria digyna*, *Bistorta vivipara* (= *Polygonum viviparum*), *Pedicularis hirsuta*, *Stellaria crassipes*, *Saxifraga oppositifolia*, *Saxifraga hieracifolia*, *Saxifraga hirculus*, *Alopecurus borealis*, *Poa alpina*, *Luzula confusa*, *Carex misandra*, *Festuca rubra*, *Equisetum arvense*, *Peltigera aphtosa* (lichen).

Collected peat cores were stored in open PVC tubes, (Ny Ålesund, Isdammen, Stuphallet) kept at 0 °C on Svalbard and after air transport and delivery, lasting less than 24 h, the peat cores were kept frozen at −20 °C. Subsampling for pollen analysis was performed on the defrosted peat core.

Core age and time resolution

Samples of organic material were sampled from the peat profile and C-14 dated by the Centrum voor Isotopen Onderzoek (CIO), Rijks Universiteit Groningen. Obtained radio-carbon age data (years BP) were transferred to Calender years BC using the cal25 programme (van der Plicht 1993):

Peat profile site	Radio carbon age Years BP (1950)	Calendar years BC (1 σ (sigma) confidence level)
GrN-28890	4670 ± 60 BP	3517 –3482 cal BC
Blomstrand		3479 –3369 cal BC
Collected July 2002		
GrN-28891	5710 ± 150 BP	4718 –4443 cal BC
Stuphallet		4421 –4395 cal BC
Collected July 2002		4387 –4371 cal BC
collected		
GrA-20057	280 ± 45 BP	1521 –1579 AD
Ny Ålesund		1583 –1594 AD
Collected August 2000		1619 –1558 AD
GrA-20058	101 ± 6 BP	1689 –1731 AD
Ny Ålesund		1808 –1826 AD
Collected August 2000		1829 –1892 AD
		1908 –1924 AD

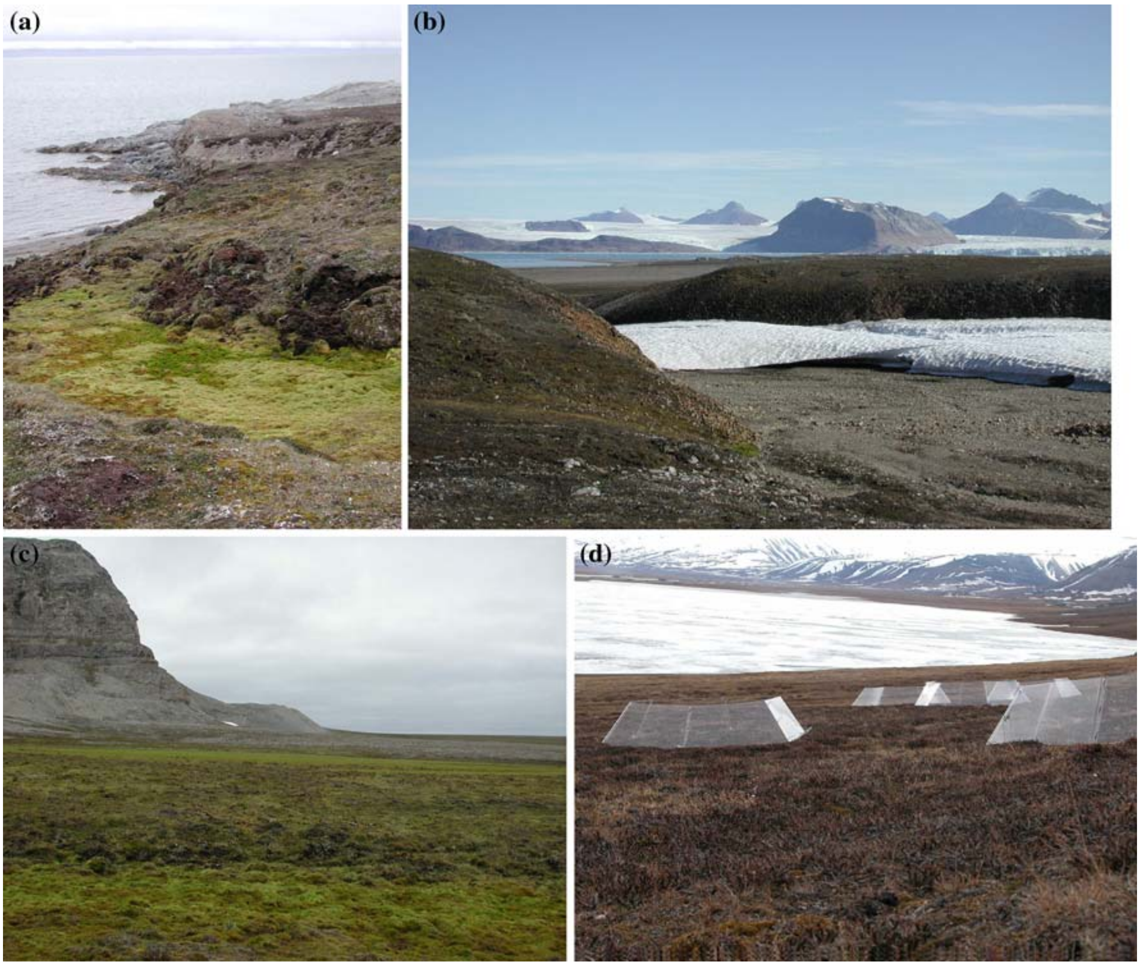

Figure 4. (a) Landscape and vegetation of (a) the Blomstrandhalvøya with the edge of the peat area bordering Kongsfjorden, (b), the Ny Ålesund arctic bell heather site, with Kongsfjorden and the Tre Kronar at the background, (c) the arctic peat in front of the Stuphallet birdcliffs, (d) *Cassiope tetragona* dominated Adventdalen glacier valley slope at Isdammen. Photographs J.Rozema.

Ny Ålesund

For a core taken 20 cm next to this core, which was about 1.5 cm shorter, the ^{14}C age has been determined at 101 ± 6 BP at 4.2 cm below the top and 280 ± 45 years BP at a depth of 5.7 cm below the soil surface. Based on these measurements the age of the lower part of the core of Ny Ålesund (9.7 cm) is estimated between 350 and 490 BP. With subsamples of 3 mm thick for acetolyis treatment and a core length of 9.7 cm the time resolution of the palynological analyis is estimated at 10–15 years for this core.

Blomstrand

A core taken at Stuphallet by van der Knaap (1988a) was dated at 45 cm depth at about 1900 years BP. Present-day Blomstrand is comparable to Stuphallet, a nutrient enriched environment at the foot of steep bird clifs. The age of the Blomstrand core has been ^{14}C estimated at 4670 ± 60 BP at a depth at 65.2–67.4 cm.

With 0.8–2.2 cm thick subsamples for acetolysis treatment and a core length of 67.4 cm the time resolution of the palynological analysis is much larger than for the Ny Ålesund core.The volume of the subsamples for the acetolysis treatment varied from 2.2–4.4 cm^3. Forty seven subsamples were taken and analysed from the core.

Stuphallet

The age of the Stuphallet core has been ^{14}C estimated at 5710 ± 150 BP at a depth of 103.7–105 cm. This value agrees reasonably well with ^{14}C dating of a similar core of precisely the same location by van der Knaap et al. 1988a: a Stuphallet 2 core was dated at 4300 ± 100 BP at 90 cm depth, estimated to have an age of 5020 BP at 105 cm after extrapolation. Subsamples for acetolysis were 1.3 cm thick.

Isdammen

This core still has not been ^{14}C dated. Since this core (19 cm) is longer than the core from Ny Ålesund (10 cm) and shorter than the core from Blomstrand, the core age is estimated to be between 700–980 years BP, under the assumption of accumulation rates similar to the Ny Alesund site.

Acetolysis, pollen identification

Acetolysis treatment of the peat profile subsamples was done according to Moore et al. (1991). Pollen were identified using Faegri and Iversen (1989) and Moore et al. (1991) as well as by comparison with light microscopy and scanning electron microscopy images of modern pollen as described in Rozema et al. (2001a, b) (Figure 5). Collection of present-day pollen of arctic tundra species was conducted during the summers of 2000–2004 at Adventdalen and Isdammen.

For calculation and graphic presentation of the pollen data Tilia and Tilia Graph (Grimm 1992) software was used.

Lycopodium marker solution

500 tablets were put into an 800 ml beaker and HCl 10% was added, as much as necessary and a solution of 1 tablet/ml was obtained. After dissolving it was topped up with water and left to settle overnight. The next day the clear liquid was decanted. The procedure was repeated one more time. The solution was transferred quantitatively into a 500 ml flask. It was topped up to 500 ml exactly and mixed thoroughly. The freshly mixed solution was transferred into an 800 ml beaker. It was stirred with a magneto stirrer while the required volume was added to the sample beakers.

Results and interpretation of the pollen record

For interpretation of the pollendiagrams obtained we use plant- climate and environment relationships as specified in Table 1.

Ny Ålesund (Figure 6)

Zone NyA-1 (9.7–9.55 cm) and NyÅ – 2 (9.7–7.75 cm)

These zones contain a herb dominated vegetation in which tussocks of *Saxifraga nivalis* and *Saxifraga oppositifolia*, pioneers of bare ground are prominent. Among the other pioneer taxa are *Cassiope tetragona*, Cyperaceae and Caryophyllaceae. The combination of *Saxifraga opppositifolia* and Caryophyllaceae indicates cold and dry conditions with poor soils (van der Knaap 1985,

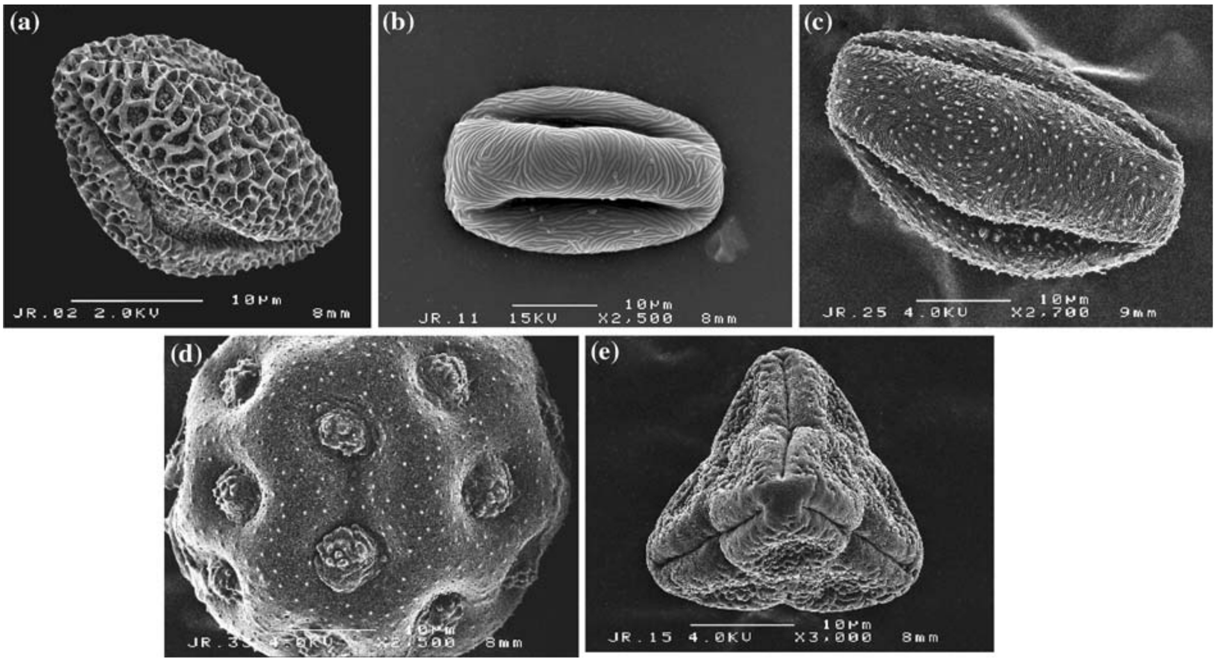

Figure 5. Scanning Electron Microscopy pictures of recent pollen grains. (a) *Salix polaris*, (b) *Saxifraga oppositifolia*, (c) *Saxifraga hirculus*, (d) *Cerastium arcticum*, (e) *Cassiope tetragona*.

1988a, b; Birks 1991; Elvebakk 1997; Rønning 1996). The presence of silt in the lower part of the profile indicates a pioneer vegetation colonising a (partly) barren landscape. Towards the top of zone NyÅ-2, *Cassiope tetragona* shows a clear increase indicating milder summer temperatures. Simultaneously the colonisation of the landscape proceeds with the spread of *Salix polaris*.

Zone NyÅ – 3 (7.75–5.65 cm)

A further colonisation by *Salix polaris* (60–75%) at the expense of the Caryophyllaceae, *Saxifraga oppositifolia* and the Cyperaceae is observed. Towards the top of this zone *Cassiope* rapidly declines and *Salix* starts to become dominant in the vegetation suggesting a rise in temperature. At the start of this zone, *Saxifraga hirculus* and Lamiaceae (Labiatae) occur temporarily.

Zones NyÅ 1–3

The increase of *Salix polaris* and the decrease of the tundra herbs might indicate a succession from tundra herbs to *Salix polaris*, possibly caused by warming of the climate or it might indicate a recolonization of the landscape after disappearance of an ice-sheet.

Zone NyÅ – 4 (5.65–4.75 cm)

The stable high values of *Salix polaris* coincide with the appearance of moss peat in the lithology. The transition to moss peat occurs at 5.8 cm and was dated to 280 ± 45 BP.

In this zone also the continuous curve of *Pinus* starts. *Pinus* does (and did not) not occur on Svalbard and this pollen must therefore originate from long distance dispersal.

The tundra herbs dominating below this have a low proportion, only Cyperaceae pollen increases slightly. The appearance of *Oxyria digyna* suggests nutrient-rich soils (van der Knaap 1988a).

Zone NyA-5 (4.75–3.55 cm)

The curves of Cyperaceae, *Casssiope tetragona* and Caryophyllaceae show a small peak, when *Salix polaris* decreases. *Oxyria* and *Saxifraga oppositifolia* are low or absent.

Zone NyA-6 (3.55–1.45 cm)

Salix polaris is still the predominant species. Cyperaceae, *Casssiope tetragona* and Caryophyllaceae are present in very low amounts. *Oxyria* and *Saxifraga oppositifolia* even disappear, although

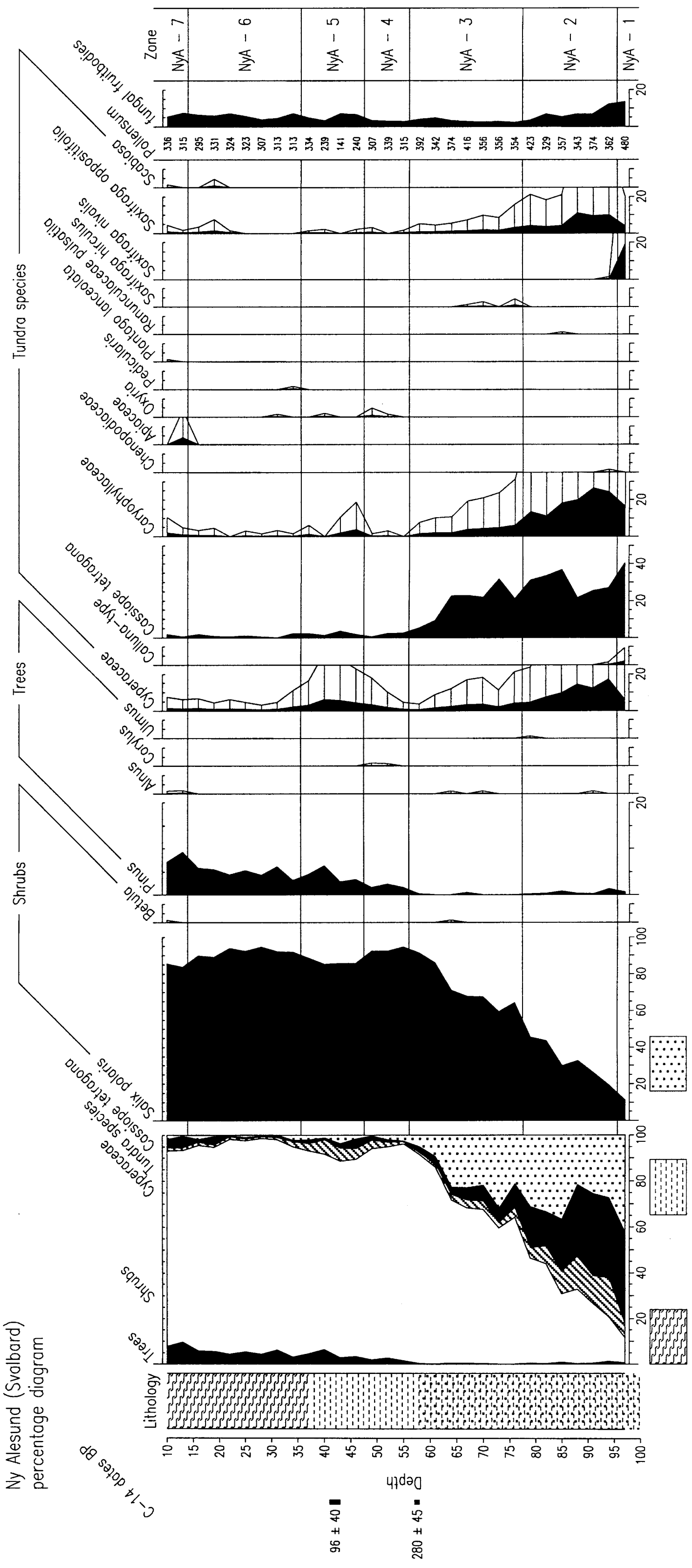

Figure 6. Percentage pollendiagram of the Ny Ålesund peat core.

Saxifraga oppositifolia appears again. This suggests relatively warm and wet conditions.

Zone NyA-7 (1.45 cm-top)
Salix polaris shows a small decrease. Apiaceae (Umbelliferae) and *Plantago lanceolata* pollen appear in this zone. The presence of *Plantago lanceolata* may be the result of human influence, which also could explain a decrease in the amount of *Salix polaris* pollen. However, *Plantago lanceolata* can also be considered a long-distance transported species (van der Knaap 1991).

An overview of the results indicates a succession from tundra herbs starting with cold adapted tundra species followed by a warmer period and an increase of the nutrient supply. Once *Salix polaris* had reached a constant high level and dominance, locally varying conditions resulted only in small variations in the assemblage.

Blomstrand (Figure 7)

Pollen numbers in some samples of the peat core have been very low and variable, and these results can therefore only be used to a limited extent as an indication of vegetation, environmental and climate changes.

Zone I (67.4–62.8 cm)
This zone dated at 4670 BP is characterized by a decrease in *Salix polaris* pollen (50–22.5%), which may indicate drier and colder conditions (van der Knaap 1989a). This might also explain the increase in *Saxifraga oppositifolia* (van der Knaap 1985; van der Knaap 1988a; b; Birks 1991). The relative increase in *Brassicaceae* suggests nutrient enrichment. Furthermore there is a decrease in the percentage and pollen number of *Saxifraga stellaris.*

Zone II (62.8–55.75 cm)
This zone is characterized by a maximum in the percentage of *Salix polaris* pollen, suggesting wetter conditions. This maximum is accompanied by a decrease in all tundra herb species. At the end of the zone *Salix polaris* decreases again and tundra herbs increase.

Zone III (55.75–46.4 cm)
In this zone *Salix polaris* pollen increase and *Brassicaceae* decrease, indicating wetter and less nutrient-rich conditions. The percentages of Cyperaceae and Gramineae pollen seem to be stable. *Saxifraga oppositifolia* starts higher than in zone II, but shows a decrease, which may be caused by warmer and wetter conditions. *Saxifraga stellaris*, a species which nowadays occurs at wet and cool sites (site 3), seems to increase, and *Koenigia islandica* appears.

Zone IV (46.4–36.8 cm)
This zone is characterized by a high and stable percentage of *Salix polaris* pollen (ca. 50%), suggesting relatively wet conditions. The pollen concentration diagram shows a decrease of the number of *Salix polaris* pollen at the end of the zone. However, the other species show a decrease as well, which results in a decrease in total pollen concentration. The number of *Poaceae (Gramineae)* pollen increases and *Cassiope tetragona* appears.

Zone V (36.8–25.4 cm)
This zone shows fluctuations in both *Salix polaris* and the tundra herb pollen. The percentage of *Salix polaris* is lower than in the previous zone. In the pollen concentration diagram it can be seen that the concentration of *Salix polaris* decreases slightly. Poaceae (Gramineae) decrease as well, and *Caryophyllaceae* disappear in this zone.

Zone VI (25.4–13.95 cm)
This zone is characterised by a low percentage of *Salix polaris* pollen and a high percentage of *Brassicaceae* pollen, suggesting nutrient rich conditions. However, the total pollen concentration is decreasing and the concentration of *Brassicaceae* starts very high, but decreases towards the end. *Cyperaceae* decrease, peaks of *Saxifraga oppositifolia* and *Saxifraga stellaris* may be the result of a cooling in temperature. *Gramineae* have disappeared; only a small peak can be noted. The pollen numbers in the last three peat subsamples are very low.

Zone VII (13.95–10.5 cm)
In this zone there is a transition from *Salix polaris* and *Saxifraga granulata* to *Brassicaceae* and *Cyperaceae*, indicators of a higher nutrient supply, to *Saxifraga stellaris* and *Papaver dahlianum*, which may be caused by a lowering in temperature.

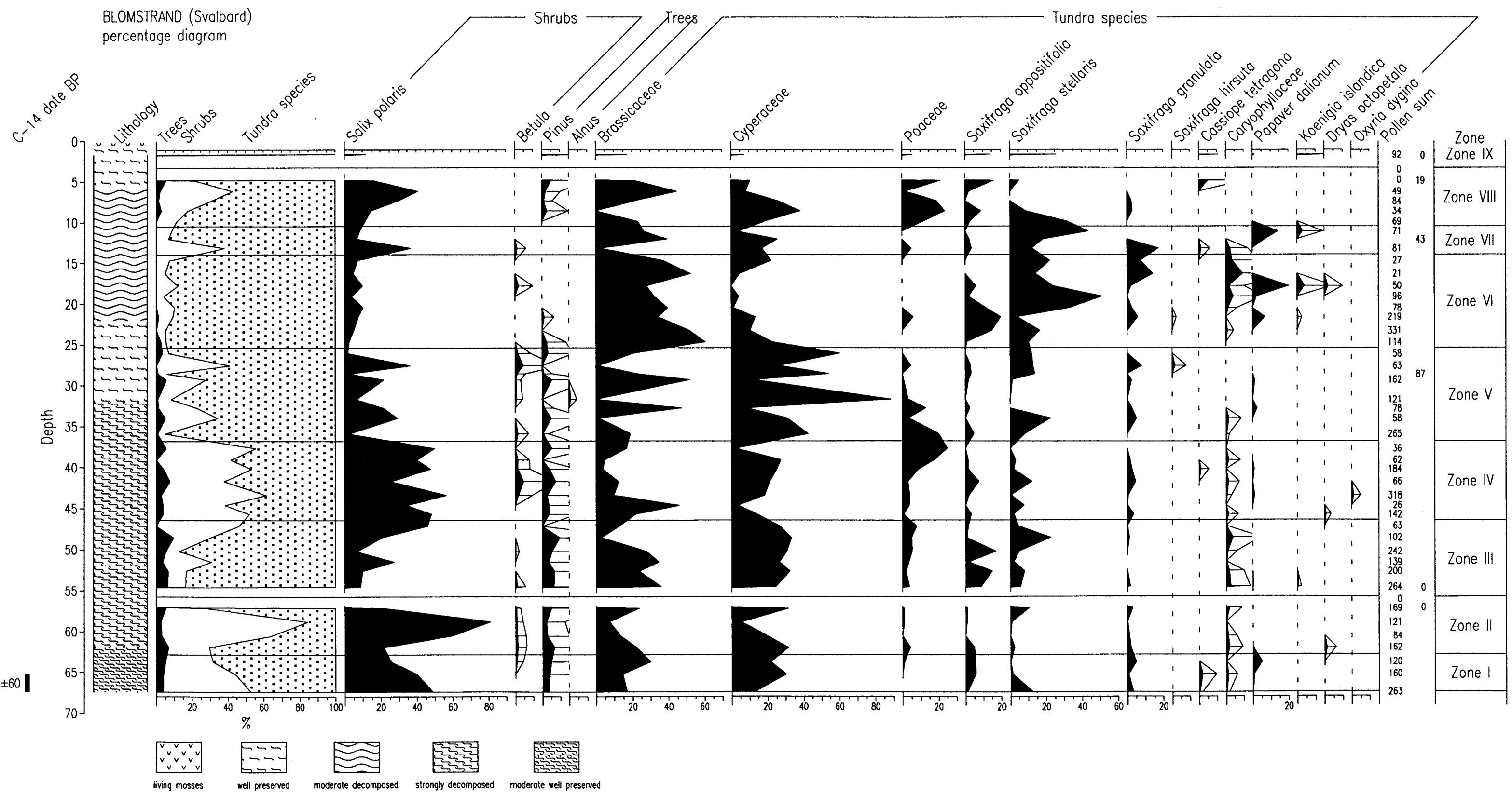

Figure 7. Percentage pollendiagram of the Blomstrand peat core.

Zone VIII (10.5–3.3 cm)
This zone is marked by a decrease in total pollen concentration. The proportion of Poaceae (Gramineae) pollen is higher than in the previous zone.

Zone IX (3.3cm-top)
This zone includes only one peat subsample per sample, i.e. the top layer of the core. The pollen numbers of the tundra species are higher than in the previous zones.

Pinus pollen are present in zone I–V
They disappear in zone VI. *Pinus* appears again in zone VIII again. The percentage is about 5% in these zones. *Pinus* is a long-distance transported pollen type (van der Knaap 1987, 1989b) and could be present because of afforestation in Europe.

In the Blomstrand peat profile, *Salix polaris*, *Brassicaceae* and *Cyperaceae* appear to be present in relatively high pollen numbers throughout the entire period. Conditions might have been wet and nutrient rich; local environmental variations may have resulted in variations in the diagram. Because of the low numbers of pollen grains in some intervals interpretation should be restrained.

Stuphallet (Figure 8)

Total pollen sum was very low and varied markedly. Only half of the 80 peat sampling intervals have been analysed. At a depth of 95–100 cm, there was an ice layer in the core. Brassicaceae pollen dominate the pollen diagram for the entire period and appear to increase the last thousands of years, reflecting the continuous input of nutrients by bird droppings from the nests on the nearby bird cliffs. Cyperaceae also occur the entire profile, in addition to *Saxifraga granulata* and *Saxifraga stellaris* and *Salix polaris*.

Isdammen (Figure 9)

Zone ISD-1 (19–13.2 cm)
In this zone *Salix polaris* dominates, indicating wetter conditions (van der Knaap 1989a). Proportions of the tundra herbs are more or less constant.

Zone ISD-2 (13.2–9.2 cm)
A decrease of *Salix polaris* and an increase of *Cyperaceae*, *Gramineae*, *Cassiope tetragona* and *Oxyria* can be seen. *Cassiope tetragona* suggests a milder climate (Rønning 1996; Elvebakk 1997), the increase of *Gramineae* and *Oxyria* also suggest richer soils (van der Knaap 1988a, b).

Zone ISD-3a (9.2–7.4 cm)
At the beginning of this period there is a decrease of *Cyperaceae*, *Gramineae* and *Cassiope tetragona*, and *Papaver dahlianum* and *Dryas octopetala* appear, suggesting colder conditions (Elvebakk 1997).

Zone ISD-3b (7.4–5.2 cm)
The peaks of *Caryophyllaceae*, *Oxyria* and *Saxifraga oppositifolia* may indicate colder conditions combined with a small decrease of *Salix polaris*.

Zone ISD-4 (5.2–3.2 cm)
Proportions of *Salix polaris* are relatively high and *Caryophyllaceae*, *Oxyria* and *Saxifraga oppositifolia* are low. *Salix polaris* dominates, which suggests higher temperatures and wetter conditions.

Zone ISD-5 (2.7 cm-top)
There is a small decrease of *Salix polaris* and a small increase of *Cassiope tetragona*. Proportions of *Saxifraga oppositifolia* are very low, indicating a warmer period.

In summary *Salix polaris*, indicating rather wet and warm conditions, dominated the environment. Some relatively brief periods of cooling and drying may have caused *Saxifraga oppositifolia* and *Caryophyllaceae* to increase, while during warmer periods *Cassiope tetragona* increased.

Discussion

Peat formation in the high Arctic

Peat formation under high Arctic or Antarctic climate conditions with very limited plant growth, is not common. Generally, optimal conditions for peat formation are annual mean temperatures between 5–10 °C (Clymo 1998). The mean annual temperature on the West-coast of Svalbard is currently about −6 °C. Another factor supporting peat formation is deficient drainage. Because of

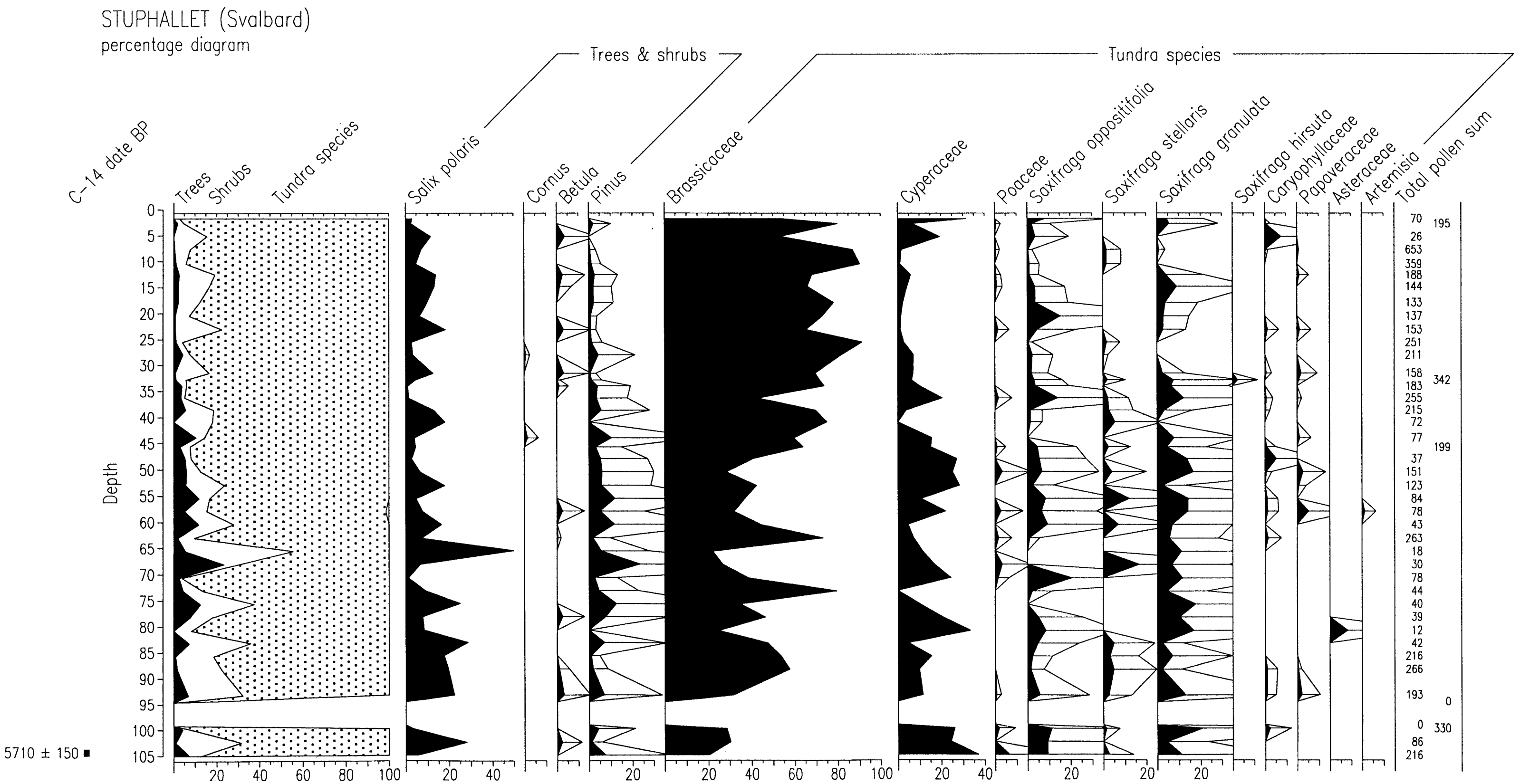

Figure 8. Percentage pollendiagram of the Stuphalllet peat core.

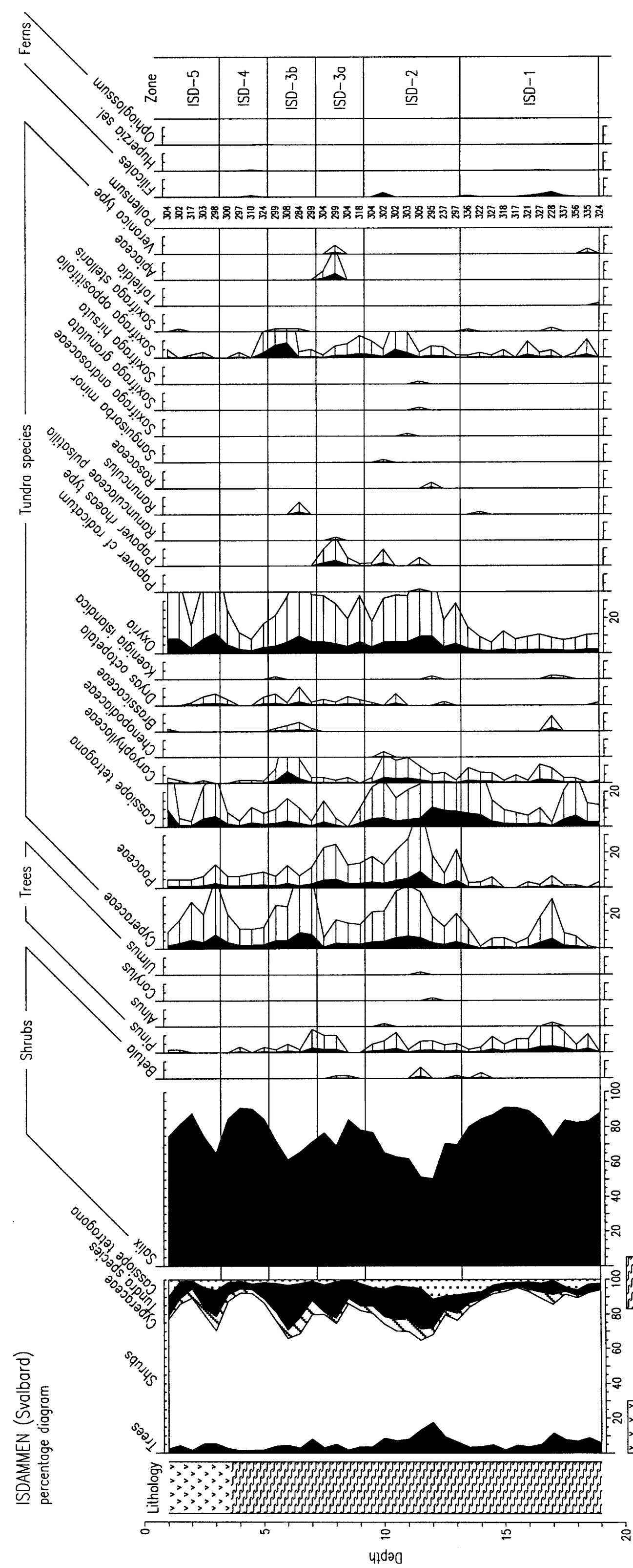

Figure 9. Percentage pollendiagram of the Isdammen peat core.

the permafrost present all over Svalbard, and soil melt-water in the summer period, the wet tundra soil is waterlogged. This leads to oxygen deficiency, which, together with low arctic temperatures strongly delays the decomposition of organic material (Bliss and Wiegolaski 1973; Stolbovoi 2002).

Peat formation on Svalbard seems to be increased in the environment of the bird cliffs (van der Knaap 1988b). Due to massive guano deposits, the nutrient concentration in the soil moisture increases supporting the enhanced development of peat forming vegetation. *Brassicaceae*, like *Cochlearia* and *Draba* are predominant taxa in the Blomstrand profile, indicating high nutrient availability (van der Knaap 1988a). This is comparable to the pollen records reported by van der Knaap (1985) at Stuphallet, a location under a bird cliff close to Blomstrand. The tundra vegetation at Stuphallet also reflects nutrient enriched soil conditions.

Permafrost soil conditions support good preservation of the peat layers. Discovering and coring peat core sections sufficiently long to represent most of the Holocene (last 10,000 years) is difficult. Many sites in the Arctic contain only peat core sections of approximately 2500 years of age or less (Boulton et al., 1976; Short and Andrews 1980; Ovenden 1988).

Pollen numbers in arctic peat

A general problem with Arctic palynology is the low concentration of pollen in the samples and consequently low pollen counts in the slides (Birks 1991).

For this reason paleo-reconstruction of arctic climate and environment is more often derived from lake deposits in limnological studies, where pollen, spores and macrofossil plant remains may accumulate (Birks et al. 2004).

Pollen concentrations were obviously low in the Blomstrand core (Figure 7) van der Knaap (1985) found similarly low pollen number in the Stuphallet peat core, in an environment, like Blomstrand, with continuous nutrient supply (guano) from adjacent birdcliffs. There is a ridge of smaller and larger stones between the foot of the bird cliffs and the Kongsfjorden. The area is relatively flat, the active layer in the summer was about 20 cm deep and both the melt water and rain caused waterlogged conditions. The nutrient supply and moist conditions allow abundant plant growth of some arctic plants, but with only few flowering plant species.

Pollen numbers were relatively high in the Ny Ålesund and Isdammen peat core. Flowering and the production of tundra plant species may be limiting factors, in addition to the low cover of tundra species.

Vegetational, environmental and climate history of Arctic Svalbard 5000–6000 years BP

The soil cores taken at Ny Ålesund, Blomstrand, Stuphallet and Isdammen are all estimated to be younger than 5760 years, i.e. representing the later part of the Holocene, which started about 10,000 years ago. The Holocene has been a relatively warm period, probably an interglacial between two ice-ages (Svendsen and Mangerud 1992, 1997). However, there have been both warmer and colder periods than present on Svalbard. Paleoenvironmental records from Svalbard show that in the period from ca. 9500 to 4000 years BP, summer air temperatures may have been higher and glaciers may have been smaller than in the present time (Birks 1991; Svendsen and Mangerud 1997). Circa 2500 years BP temperatures had fallen to near or below-present values and generally remained lower until the present century (Birks 1991). The relatively cold period in the interglacial Holocene lasting from about 16th to mid 19th century (Grove1988; Williams et al. 1998) is called the Little Ice Age (LIA). During the LIA glaciers expanded considerably on Svalbard (Svendsen and Mangerud 1997; Grove 2001). The uninterrupted palynological records of the peat cores presented in this paper indicate that none of the sites studied were glaciated during the period covered.

Isaakson et al. (2003) reconstructed past temperatures based on $^{18}O/^{16}O$ values of ice cores drilled in northern and north eastern parts of Svalbard for the period 1400–2000 AD. There is no evidence for an LIA decrease of Svalbard temperature at these ice core sites (far north of the sites where the peat profiles were collected), but reconstructed temperature decreased from about 1750–1850 AD, and increased from 1900–2000 AD. Since the LIA most glaciers on Svalbard have retreated because of gradual summer (and winter) warming (Svendsen and Mangerud 1997).

Despite significant temperatures changes in the Arctic regions during the past thousand years, it remains uncertain if and how these temperature changes affected plant growth and vegetation composition on Svalbard. Frost during the Little Ice Age may have strongly affected plant and vegetation in temperate climate regions such as Atlantic Europe, but may have left Arctic tundra plant growth unchanged (Van Geel et al. 1996, 1998; Mauquoy et al. 2002).

During the last 100 years a global warming has been marked (Hassol 2004). According to Karl (1998), temperatures on Svalbard increased by 4 °C from 1906 until 1996. Such a temperature increase will have caused changes in vegetation composition that may have been recorded in fossil pollen records.

On Svalbard, the climate is Arctic and the tundra plant community is adapted to the often severe conditions. These adaptations have been used to link changes in vegetation composition to climatic variations, according to climatic and environmental indicator species (cf Isarin 1997; Iversen 1954).

Possible links between changes in the Svalbard pollen records, Ny Ålesund, Blomstrand and Isdammen, and the climatic events just described will now be discussed.

The pollen record from Ny Ålesund, extrapolated to be about 490 (350) years BP old, starts about 1460 (1600) AD (Figure 8) just before or at the start of the Little Ice Age, and it is shown that low-temperature indicating species like *Saxifraga oppositifolia* (van der Knaap 1985, 1988a, b; Birks 1991; Aiken et al. 1999) and *Caryophyllaceae* species (Rønning 1996; Elvebakk 1997), but also *Cassiope tetragona* (indicating dry conditions) dominate the vegetation in that period. Towards the end of the LIA *Saxifraga oppositifolia* and *Caryophyllaceae* decrease and *Salix polaris* has come, reaching a maximum at about 1700 AD, possibly due to summer warming melting of nearby snow fields and glaciers, leading to moist glacier valley soil conditions.

It is unlikely that a glacier was located at the site, since tundra vegetation seems to have been present throughout the entire pollen record and presence and retreat of a glacier would have been indicated by silt in the core.

In the Isdammen pollen record (Figure 9) the vegetation composition seems to have been quite stable during the past centuries. *Salix polaris* dominates throughout the entire record. Also *Cassiope tetragona* occurs throughout the entire period. Brassicaceae species are almost lacking and indicate that the nutrient status of the Isdammen vegetation has been low.

Pollen numbers have been continuously high for the entire period and glaciation of the site during the period covered is unlikely. It is unclear to us why the similarly high time resolution of the Isdammen pollen diagram, likely to cover the LIA, does not clearly show changes of tundra plant species supporting this. Alternatively, no decreased temperatures may have occurred on arctic Svalbard during the LIA.

Obviously, with an improved chronology, based on more C-14 dating of subsamples of the peat profiles studied, conclusions on the relationship between arctic tundra vegetation changes before, during and after the LIA, could be developed more firmly.

Plant climate relationships, as required for a proper implementation of the Climate Indicator Species approach (Zagwijn 1994; Isarin 1997) are insufficiently developed for the Arctic. Arctic plant species distributions in the summer have been studied (Elvebakk 1994; Elvebakk and Prestud 1996; Elvebakk 1997) and mean summer or mean July temperatures may be used to explain changes in proportions of the pollen of *Salix polaris*, *Saxifraga oppositifolia* and *Cassiope tetragona*, as was done in this study. Increased growth of *Cassiope tetragona* obtained with experimental warming (1.5 °C) of tundra plants with Open Top Roofs (Figure 4d) is now being developed as a new biotic proxy of temperatures during the past (Blokker et al. in prep.; Rozema et al. in prep). As a tundra plant species of dry, relatively warm terrestrial environments, *Cassiope* growth responds to summer warming. This evergreen arctic heather shrub is also capable of surviving severe winter frost and dessication. Plant parameters linked with mean winter temperatures may also-help to reconstruct past climate regimes.

Perspective for reconstruction of past UV climate

In the present paper a palynological approach was followed to reconstruct past climate and environment, using pollen species identity and pollen numbers. For at least the last 6000 years *Salix* (cf *polaris*) has been a dominant tundra plant species.We have assumed that pollen identified as *Salix* actually represent *Salix polaris*; at the present day *Salix polaris* is by far the predominant arctic species in the Svalbard tundra, beside *S. reticulata*, *S. arctica* and *S. herbacea*. In warmer periods in the past the latter *Salix* species may have been more abundant.

For the reconstruction of past temperature and solar UV-B irradiance, both the morphological and chemical properties of pollen and macrofossil plant remains of *Salix polaris* will be further studied Rozema et al. 2002.

A proxy to reconstruct historic levels of UV-B irradiance may be the phenolic compounds found in pollen, spores, and preserved leaves and twigs of this tundra shrub (Rozema et al. 2001a, b; Blokker et al. 2005).

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References

Aerts R., Cornelissen, J.H.C. and Dorrepaal E. 2005. Plant performance in a warmer world: general responses of plants from cold, northern biomes and the importance of winter and spring events. Plant Ecol. this volume.

Aiken S.G., Dallwitz M.J., Consaul L.L., Mc Jannet C.L., Ginnespie L.J., Boles R.L., Argus G.W., Gillett J.M., Scott P.J., Elven R., Blanc M.C. le Zamluck A.E. and Brysting A.K. 1999. Flora of the Canadian Arctic Archipelago: Descriptions, Illustrations, Identification and Information retrieval.

Barkman J.J. 1987. Preliminary investigations on the texture of high arctic tundra vegetation. In: Huiskes A.H.L., Blom C.W.P.M. and Rozema J. (eds), Vegetation Between Land and Sea, Dr. W. Junk Publishers, Dordrecht, pp. 120–132.

Birks H.H. 1991. Holocene vegetational history and climatic change in west Spitsbergen – plant macrofossils from Skardtjørna, an Arctic lake. Holocene 13: 209–218.

Birks H.J.B., Jones V.J. and Rose N.L. 2004. Recent environmental change and atmospheric contamination as recorded in lake sediments – an introduction. J. Paleolimnol. 31: 403–410.

Bliss L.C. and Wiegolaski F.E. (eds). 1973. Primary Production and Production Processes, Tundra biome. Tundra Biome Steering Committee, University of Alberta, Edmonton.

Blokker P., Boelen P., Broekman R. and Rozema J. 2005. The potential of p-coumaric and ferulic acid as UV proxies: occurrence in pollen and spores, preservation and pyrolytic analysis. Plant Ecol. (this volume).

Boelen P., de Boer M. K., de Bakker N., Blokker P. and Rozema. J. 2005. Field studies on the effects of solar UV-B on polar bryophytes: overview and methodology. Plant Ecol. (this volume).

Boulton G.S., Dickson J.H., Nichols H., Nichols M. and Short S.K. 1976. Late Holocene glacier fluctuations and vegetation changes at Maktak Fjord, Baffin Island, N.W.T., Canada. Arctic Alpine Res. 8: 343–356.

Clymo R.S. 1998. *Sphagnum*, the peatland carbon economy, and climate change. In: Bates J.W., Ashton N.W. and Duckett J.G. (eds), Bryology for twenty-first Century, Maney Publishing and the British Bryological Society, Leeds, pp. 361–368.

Elvebakk A. 1994. A survey of plant associations and alliances from Svalbard. J. Veg. Sci. 5: 791–802.

Elvebakk A. and Prestrud P. (eds) (1996). A Catalogue of Svalbard Plants, Fungi, Algae and Cyanobacteria. Norsk Polar Institutt Skrifter 198: 1–395.

Elven R. and Elvebakk A. 1996. Vascular plants. In: Elvebakk and Prestrud P. (eds), A Catalogue of Svalbard Plants, Fungi, Algae and Cyanobacteria. Norsk Polar Institutt Skrifter 198: 9–95.

Elvebakk A. 1997. Tundra diversity and ecological characteristics of Svalbard. Ecosystems of the world 3, Polar and Alpine Tundra: 347–359.

Farman J.C., Gardiner B.G. and Shanklin J.D. 1985. Large losses of total ozone in Antarctica reveal seasonal CLO_x/NO_x interaction. Nature 315: 207–210.

Faegri K. and Iversen J. 1989. Textbook of Pollen Analysis. 4th ed. Faegri K., Kaland P.E. and Krzywinski K. (eds), John Wiley & Sons, New York, 328 pp.

Hassol S. J. 2004. Impact of a Warming Arctic. Arctic Climate Impact Assessment. Cambridge Universiry Press. p. 139.

Grimm E.C. 1992. TILIA and TILIA-graph: pollen spreadsheet and graphic programs. Volume of abstracts 8th International Palynological Congress, Aix-en-Provence 1992, p. 56.

Grove J.M. 1988. The Little Ice Age. Methuen, London, 498 pp.

Grove J.M. 2001. The initiation of the "Little Ice Age" in regions round the North Atlantic. Climatic Change 48: 53–82.

Hisdal V. 1985. Geography of Svalbard. Norsk Polar Institutt, Oslo, p. 75.

Hisdal V. 1998. Svalbard Nature and History. Norsk Polar Institutt, Oslo, p. 123.

Houghton J.T., Ding Y., Griggs D.J., Noguer M., van der Linden P.J., Dai X., Maskell K. and Johnson C.A. (eds). IPCC 2001. Climate Change 2001. The Scientific Basis. Cambridge University Press.

Isarin R.F.B. 1997. The climate in north-western Europe during the Younger Dryas. Ph.D. Thesis, Vrije Universiteit, Amsterdam, 159 pp.

Isarin R.F.B. and Bohncke S.J.P. 1999. Mean July temperatures during the Younger Dryas in Northwestern and Central Europe as inferred from Climate Indicator Plant Species. Quaternary Res. 51: 158–171.

Isaaksson E., Hermanson M., Hicks S., Igarashi M., Kamiyama K., Moore J., Motoyama H., Muir D., Pohjola V. and Vaikmae R. 2003. Ice cores from Svalbard-useful archives of past climate and pollution history. Physics Chemistry Earth 28: 1217–1228.

Iversen, J. 1954. The Late-glacial flora of Denmark and its relation to climate and soil. Danmarks Geologiske Undersøgelse Årbog 2: 87–119.

Karl T.R. 1998. Annex A "Regional Trends and Variations of Temperature and Precipitation". The Regional Impacts of Climate Change. IPCC WGII, Cambridge University Press.

van der Knaap W.O. 1985. Human influence on natural Arctic vegetation in the seventeenth century and climatic change since A.D. 1600 in north-west Spitsbergen: a paleobotanical study. Arctic Alpine Res. 17: 371–387.

van der Knaap W.O. 1987. Long-distance transported pollen and spores on Spitsbergen and Jan Mayen. Pollen et Spores XXIX(4): 449–453.

van der Knaap W.O. 1988a. A pollen diagram from Brøggerhalvøya, Spitsbergen: changes in vegetation and environment from ca. 4400 to ca. 800 BP. Arctic Alpine Res. 20: 106–116.

van der Knaap W.O. 1988b. Age and stability of bird-manured vegetation on Spitsbergen. Arctic Botanica Neerlandica 37: 171–179.

van der Knaap W.O. 1989a. Relations between present-day pollen deposition and vegetation in Spitsbergen. Ph.D. Thesis. Laboratory of Paleabotany and Palynology, Utrecht. Arctic centre, Groningen, pp.15–26.

van der Knaap W.O. 1989b. Deposition of long-distance transported pollen and spores since 7900 B.P. studied in peat deposits from Spitsbergen. Ph.D. Thesis. Laboratory of Paleabotany and Palynology, Utrecht. Arctic centre, Groningen. pp. 113–117.

van der Knaap W.O. 1991. Palynology of peat sections from Spitsbergen covering the last few centuries. Nordic J. Botany 11: 213–223.

Mc Peters R., Hollandsworth S., Flynn L., Herman J. and Seftor C. 1996. Long-term ozone trends derived from the 16-year combined nimbus 7/ meteor 3 TOMS version 7 record. J. Geophys. Res. 23: 3699–3702.

Moore P.D., Webb J.A. and Collinson M.E. 1991. Pollen Analysis. Blackwell Scientific, London, p. 216.

Mauquoy D., van Geel B., Blaauw M. and van der Plicht J. 2002. Evidence from northwest European bogs shows Little Ice Age climatic changes driven by variations in solar activity. Holocene 12: 1–6.

Newman P., Gleason J., Mc Peters R. and Stolarski R. 1997. Anomalously low ozone over the arctic. Geophys. Res. Lett. 24: 2689–2692.

Ovenden L. 1988. Holocene proxy-climate data from the Canadian Arctic. Geological Survey of Canada Paper: 88–122.

van der Plicht J. 1993. The Groningen Radiocarbon Calibration Program. Radiocarbon 35: 231–237.

Rozema J., Noordijk A.J., Broekman R.A., van Beem A., Meijkamp B.M., de Bakker N.V., van de Staaij J.W.M., Stroetenga M., Bohncke S.J.P., Konert M., Kars S., Peat H., Smith R.I.L. and Convey P. 2001a. Polyphenolic compounds in pollen and spores of Antarctic plants as indicators of solar UV-B: a new proxy for the reconstruction of past solar UV-B?. Plant Ecol. 154: 11–26.

Rozema J., Broekman R., Blokker P., Meijkamp B.M., de Bakker N.V., van de Staaij J., van Beem A., Ariese F. and Kars S.M. 2001b. UV-B absorbance and UV-B Absorbing Compounds (*para*-coumaric acid) in pollen and sporopollenin: the perspective to track historic UV-B. J. Photochem. Photobiol. 6: 108–117.

Rozema J., van Geel B., Björn L.O., Lean J. and Madronich S. 2002. Towards solving the UV puzzle. Science 296: 1621–1622.

Rozema J., Boelen P., Solheim B., Zielke M., Buskens A., Doorenbosch M., Fijn R., Herder J., Callaghan T.V., Björn L.-O., Gwynn Jones D., Broekman R., Blokker P. and van de Poll W. 2006. Stratospheric ozone depletion: high arctic tundra plant species from Svalbard are not affected by enhanced UV-B after 7 years of UV-B supplementation in the field. Plant Ecol. (this volume).

Rozema J., Boelen P. and Blokker P. 2005. Depletion of stratospheric ozone over the antarctic and arctic: responses of plants of polar terrestrial ecosystems to enhanced UV-B, an overview. Environment. Pollution 137: 428–442.

Rønning O.I. 1965. Studies in Dryadion of Svalbard. Norsk Polarinstitutt Skrifter 134: 1–52.

Rønning O.I. 1996. Svalbards Flora. Norsk Polar Institutt.

Short S.K. and Andrews J.T. 1980. Palynology of six middle and late Holocene peat sections, Baffin Island. Géographie physique et Quaternaire 34: 61–75.

Stolbovoi V. 2002. Carbon in Russian soils. Climatic Change 55: 131–156.

Summerhayes V.S. and Elton C.S. 1923. Contributions to the ecology of Spitsbergen and Bear Island. J. Ecol. 11: 214–286.

Steffensen E.L. 1982. The climate at Norwegian Arctic stations. Klima 5: 1–44.

Svendsen J.I. and Mangerud J. 1992. Paleoclimatic inferences from glacial fluctuations on Svalbard during the last 20,000 years. Climate Dynamics 6: 213–220.

Svendsen J.I. and Mangerud J. 1997. Holocene glacial and climatic variations on Spitsbergen, Svalbard. Holocene 7: 45–57.

Van Geel B., Buurman J. and Waterbolk H.T. 1996. Archaeological and palaeoecological indications of an abrupt climate change in The Netherlands, and evidence for climatological teleconnections around 2650 BP. J. Quaternary Sci. 11: 451–460.

Van Geel B., van der Plicht J., Kilian M.R., Klaver E.R., Kouwenberg J.H.M., Renssen H., Reynaud-Farrera I. and Waterbolk H.T. 1998. The sharp rise of Δ ^{14}C ca. 800 cal BC: possible causes, related climatic teleconnections and the impact on human environments. Radiocarbon 40: 535–550.

Williams M., Dunkerley D., De Deckker P., Kershaw P. and Chapell J. 1998. Quaternary Environments, 2nd ed. Arnold, London.

Zagwijn W.H. 1994. Reconstruction of climate change during the Holocene in western and central Europe based on pollen records of indicator species. Vegetation Hist. Archeobot. 3: 65–88.