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Climate and Vegetation of the Interior Lowlands of Southern Baffin Island: Long-term Stability at the Low Arctic Limit

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ABSTRACT. The interior of southern Baffin Island between 64˚N and 68˚N latitude is a mainly lowland area over 50 000 km^2 in extent, containing two large lakes (Amadjuak and Nettilling) and numerous smaller lakes and ponds. This area is important as summer range for caribou and a variety of birds, and there is evidence for a human presence as early as 3000 B.P. Field studies between 1984 and 1988 and the operation of climatic autostations from 1987 to 1995 revealed a warm summer climate and cold winters. There is a locally rich and diverse vegetation, including *Betula glandulosa* and other species that are indicative of the low arctic bioclimatic zone and mark the present northern limit of that zone in the eastern Canadian Arctic. Air photos and Landsat imagery were used to map vegetation beyond the field areas, leading to an estimate of 46% of the land area in continuous vegetation (tundra) of some type and 15% with shrub and heath elements. Palynology of sediment cores taken from Nettilling Lake permitted extrapolation from present bioclimatic conditions to 4750 years B.P. *Betula* and therefore elements of a low arctic vegetation association appear to have been present in the area during most of that period, indicating a local bioclimatic system that has been relatively stable under regional variations of climate.

Key words: Baffin Island, Nettilling Lake, low arctic vegetation, bioclimate, remote sensing, palynology, automatic climate station, climate change

RÉSUMÉ. La région intérieure du sud de la terre de Baffin située entre le 64˚ et le 68˚ de latit. N. est essentiellement une zone de basses-terres s'étendant sur plus de 50 000 km^2, qui renferme deux grands lacs (Amadjuak et Nettilling) et de nombreux petits lacs et étangs. Cette région est importante en tant que territoire estival du caribou et d'une diversité d'oiseaux, et on y a découvert des preuves attestant une présence humaine dès 3000 BP. Des études sur le terrain menées entre 1984 et 1988 et l'activité de stations climatologiques automatisées de 1987 à 1995 ont révélé un climat d'été tempéré et d'hiver froid. La végétation locale est riche et diversifiée et comprend *Betula glandulosa* ainsi que d'autres espèces typiques d'une zone bioclimatique du Bas-Arctique et marquant la limite septentrionale actuelle de cette zone dans l'Arctique canadien oriental. Des clichés aériens et des images du satellite Landsat ont servi à cartographier la végétation au-delà des zones d'étude sur le terrain, ce qui a amené à une estimation de 46 p. cent de la zone possédant un couvert végétal continu (toundra) d'une certaine sorte et 15 p. cent possédant des composants d'arbrisseaux et de bruyère. La palynologie de carottes de sédiments provenant du lac Nettilling a permis d'extrapoler les conditions bioclimatiques depuis la période actuelle jusqu'à 4750 ans BP. Il semble que *Betula* et par conséquent des composants d'une association végétale du Bas-Arctique ont été présents dans la région pendant la plus grande partie de cette période, ce qui révèle l'existence d'un système bioclimatique relativement stable à l'intérieur de variations climatiques régionales.

Mots clés: terre de Baffin, lac Nettilling, végétation du Bas-Arctique, bioclimat, télédétection, palynologie, station climatologique automatisée, changement climatique

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INTRODUCTION

Understanding present and past relationships between climate and vegetation in the Arctic is a prerequisite for projections about future climate and impacts of climate change on terrestrial ecosystems and renewable resources. The record of vegetation responses to climate change is expected to be most evident in transitional zones, i.e., ecotones. In the Arctic, the most obvious such feature is the forest-tundra ecotone (Larsen, 1989; Sveinnbjornsson, 1992); however, other vegetation zones north of the tree line may be equally significant in the context of vegetation responses to climate change (Young, 1971; Edlund and Alt, 1989). We present here the results of studies of the climate and vegetation in

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such an arctic transitional zone, the interior lowlands of southern Baffin Island (Fig. 1).

Some maps of the vegetation zones or bioclimatic regions of the eastern Canadian Arctic show the interior of southern Baffin Island to be an outlier of the continental "low arctic" (Polunin, 1948) or "arctic dwarf shrubs-sedges-lichen-heath" (Porsild, 1951). Accordingly, the northern limit of this zone is approximately on the Arctic Circle at Nettilling Lake. The extent of the low arctic zone in Baffin Island, as indicated by the presence of dwarf birch (*Betula glandulosa* Michx. and *B. nana*), became the subject of studies starting in the 1970s, with investigations on Davis Strait (Andrews et al., 1980) and Frobisher Bay (Jacobs et al., 1985), where the birch distribution was found to be confined to a coastal fringe. From those results, it was estimated that the actual extent of modern "low arctic" shrub tundra in southern Baffin Island is less than 10% of the total land area (Jacobs, 1988).

The reported presence of dwarf birch and other low arctic species near the Arctic Circle at the head of Cumberland Sound (Soper, 1928), and an inferred positive summer temperature anomaly extending inland from Frobisher Bay (Maxwell, 1980), led us to suspect that low arctic vegetation elements might be present in the vicinity of Nettilling and Amadjuak Lakes (Fig. 1). A list of plants collected by J.D. Soper at Nettilling Lake in 1925 provided support for this interpretation. Some 60 species are represented in his collection, including taxa characteristic of the low-to-high arctic transition zone; however, he did not report finding *Betula* there (Soper, 1926, 1928). Our preliminary field surveys in the Nettilling Lake area during 1984 and 1985 confirmed the existence of a low arctic flora, including *Betula glandulosa*, at the south end of the lake. This discovery prompted questions about the spatial extent and history of the vegetation and the associated climate. Field work in 1986 and 1987 included surveys and collections to better define the regional vegetation, retrieval of lake sediment cores and modern pollen samples for palynological analysis, and climatological observations, including installation of automated climatological stations at Nettilling Lake and Amadjuak Lake. Subsequent work consisted of annual site visits to service the climate stations and the acquisition and analysis of satellite imagery of the area. The observational program ended in July 1995 with the removal of the climate autostation from Amadjuak Lake. Details of the 8-year climatological program will be presented elsewhere. Here we report the results from the standpoint of contemporary regional climate-vegetation relationships and what can be inferred from the palynological record about conditions in the past.

PHYSICAL SETTING

The interior and coastal lowlands of southern Baffin Island comprise the Foxe Lowland physiographic province, which is bisected by a major contact between Ordovician sedimentary rocks and Precambrian granite-gneiss, overlain with

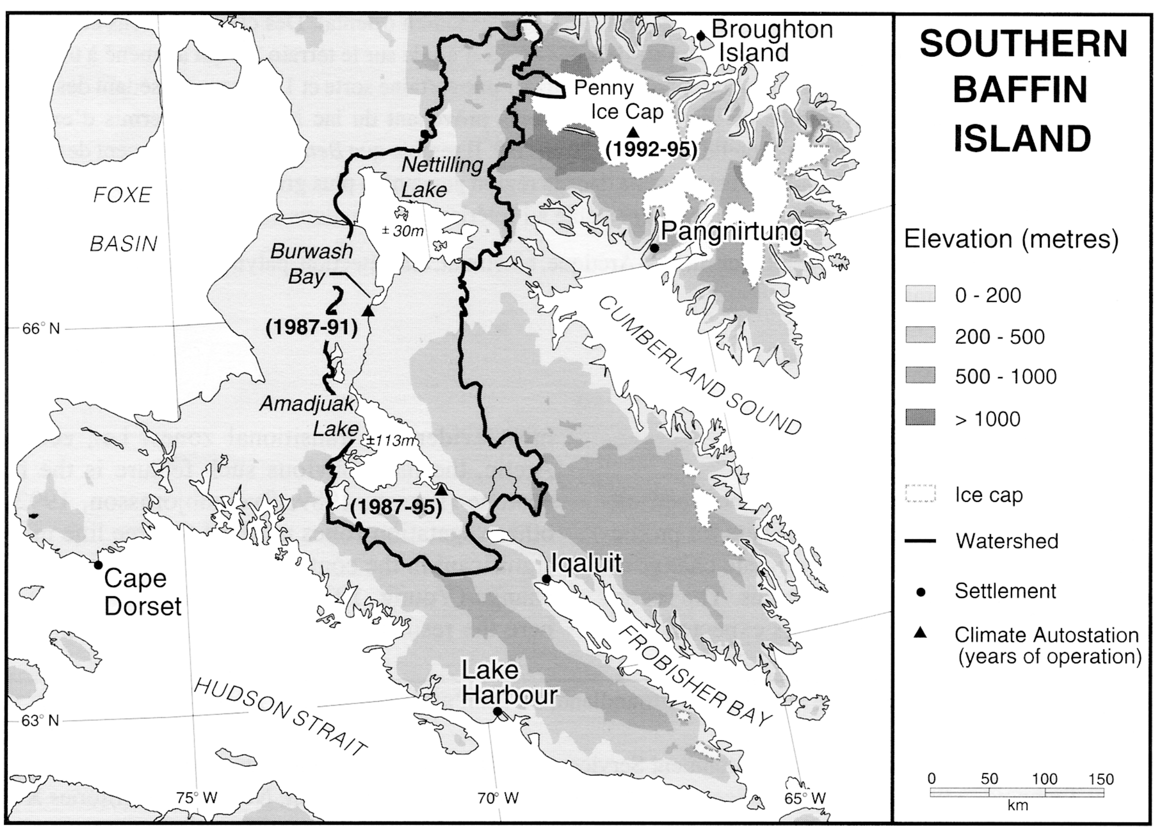

FIG. 1. Map of Southern Baffin Island, showing study area, climate autostation sites, and places referred to in the text.

extensive glacial, glaciofluvial, and marine sediments (Blake, 1966; Blackadar, 1967). The interior between 64˚N and 68˚N latitude is an extensive lowland containing two large lakes, Amadjuak and Nettilling, and many smaller lakes and ponds (Fig. 1). The large lake system drains westward through the 74 km length of the Koukdjuak River to Foxe Basin. Nettilling Lake, with an area of 5542 km^2, is the largest freshwater body in the Canadian Arctic Archipelago, and both lakes are large enough to have a significant influence on the climate of their surroundings (Jacobs and Grondin, 1988).

From digital planimetry, the combined drainage basin area of Amadjuak Lake and Nettilling Lake (Fig. 1) was found to be 52 970 km^2. The hypsometric characteristics of the drainage basin were estimated from a subset of the "TerrainBase" 5-minute global digital elevation model (Row et al., 1995). The highest grid square within the basin is on the northwest side of Penny Ice Cap (Fig. 1) at 1520 m a.s.l. However, the median elevation of the 5-minute grid squares is 173 m a.s.l., with 90% found to be below 400 m and 23% below 100 m.

At 30 m a.s.l., Nettilling Lake is below the regional maximum postglacial marine limit of 93 m, dated about 6700 B.P. (Blake, 1966). The immediate postglacial history of the Nettilling Lake area is one of marine inundation ca. 7000 B.P., followed by emergence and the establishment of the current freshwater regime by 5000 B.P. Amadjuak Lake (113 m a.s.l.) is above the marine limit and was formed approximately 4500 years ago in proximity to a waning ice cap remnant (Blake, 1966).

Southern Baffin Island is generally viewed as being within the continuous permafrost zone (Heginbottom, 1984). From limited probing and shallow pits at the south end of Nettilling Lake, we found active-layer depths to range from less than 0.5 m in poorly drained areas to nearly 2 m in the coarse sands and gravels of elevated glacio-lacustrine deposits. The effect on soils of contrasting parent rocks on the east and west sides of the lake is blurred by the surficial glacial and marine-lacustrine deposits. The soils that have developed from the marine-lacustrine sedimentary deposits around the lake shore appear to be azonal and acidic.

The area extending from Amadjuak Lake northward to beyond Nettilling Lake is a major summer feeding ground and migration route for caribou (Ferguson, 1989) and a nesting area for a variety of birds. There is archaeological evidence for a human presence as early as 3000 B.P., including significant autumn use by Thule Culture people (Jacobs et al., 1990; Stenton, 1991). The region is still important to the Inuit hunting economy (Stenton, 1991).

There are no permanent meteorological stations in the interior of southern Baffin Island. Early reports such as those of Hantszch (1911, in Neatby, 1977) and Soper (1928, 1981) indicated winters of intense cold and wind, with a continuous, hard snowcover, and short, warm summers with dense clouds of mosquitos. From general climatological considerations and extrapolation from coastal stations, Maxwell (1980) inferred locally elevated summer temperatures (greater than 7.5˚C in July) in the Nettilling Lake area.

The principal field area for this study was Burwash Bay, a shallow, constricted embayment at the south end of Nettilling Lake (Fig. 1). The surrounding land is of generally low relief, rising to little more than 100 m above the bay in any direction (Fig. 2). The most conspicuous relief features in the Burwash Bay area are east-west trending recessional moraines, several of which are partly submerged and nearly cut the bay off from the deeper, main body of the lake. Inflow to Burwash Bay is mainly from the Amadjuak River, with several smaller streams contributing flows from localized peripheral drainage areas. Ice is present in Nettilling Lake as late as early August in most years, but the influx of relatively warm water from the Amadjuak River causes Burwash Bay to clear several weeks earlier than the main body of the lake (Jacobs and Grondin, 1988). The numerous shallow ponds in the area thaw by early July and are frequented by waterfowl.

METHODS

Climatology

Meteorological instruments were installed in 1987 at Burwash Bay and on Amadjuak Lake, 154 km to the south (Fig. 1). The installations followed Canadian standards for climatic autostations (Atmospheric Environment Service, 1992a); therefore, these measurements are considered to be equivalent for purposes of comparison to those made at permanent (staffed) stations in the region. Elements recorded were air temperature and humidity at 2 m above the ground, wind speed and direction at 3 m, ground temperature at 10 and 20 cm depth, and total solar radiation. Precipitation was measured only at the Amadjuak Lake site, by means of a Fischer-Porter weighing gauge fitted with a Nipher shield. Air temperature was measured with a resolution of 0.1˚C and a nominal uncertainty of ± 0.1˚C (Atmospheric Environment Service, 1992a). The estimated RMS error in average daily totals of solar radiation was less than 5% in the period June through September and about 10% in the remainder of the year. Data were recorded every three hours at both locations. The sites were visited in July of each year, at which time data were downloaded and the equipment repaired or replaced as necessary. Details concerning the autostation installations have been reported elsewhere (Jacobs et al., 1993).

Vegetation Studies

On the basis of limited prior information about summer temperatures, we expected that low arctic tundra species, particularly *Betula glandulosa*, would be found in areas of suitable soils in the vicinity of Nettilling Lake. The main focus of field activities was therefore the area surrounding Burwash Bay (Fig. 1), although the reconnaissance extended along the entire western shore of Nettilling Lake as well as to an area within a radius of about 10 km from the climate autostation site at the south end of Amadjuak Lake. Travel within the study area was by small boat and on foot. The

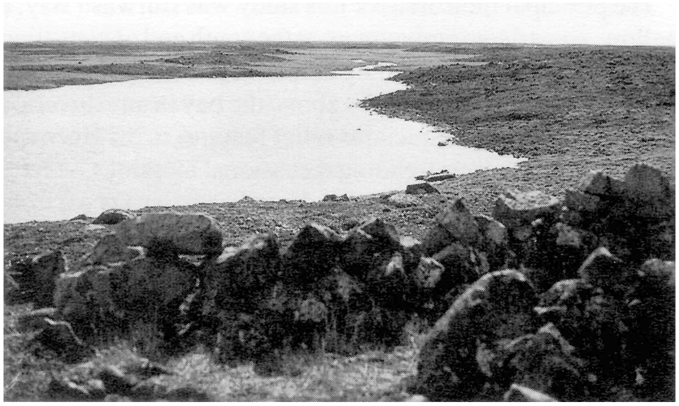

FIG. 2. View inland from the east side of Burwash Bay. The stream in the background drains granite-gneiss bedrock, which supports extensive heath with occasional *Betula glandulosa*. Lake sediment cores described in the text were taken from this inlet. The structure in the foreground is one of many in the area associated with the Inuit caribou hunt.

approach to vegetation studies in the region was principally of a reconnaissance nature; the vegetation was noted and voucher specimens were collected. In addition to identifying plants, we made an effort to distinguish and describe generalized vegetation-landscape units. In 1986, an intensive collecting effort was undertaken at Burwash Bay in collaboration with Dr. Susan Aiken of the Canadian Museum of Nature, and lists and voucher specimens from these collections were placed in the National Herbarium, Canadian Museum of Nature, Ottawa.

As part of a larger study concerned with differences in vegetation composition across the low arctic zone in Baffin Island (Maus, 1987), quadrat analysis was carried out on a low, south-facing slope in the vicinity of the Burwash Bay climate station. Sampling was done on three 50 m transects spaced 25 m apart and aligned parallel to the slope. A 0.5 m by 0.5 m quadrat was placed randomly within each 5 m interval of a transect, for a total of 10 quadrats per transect. The proportion of cover by species (i.e., density) was estimated within each 2 cm by 2 cm cell of the grid. Environmental data, soil samples, and voucher specimens were collected for each quadrat (Maus, 1987). For purposes of comparison, the same sampling strategy was used at sites near the communities of Pangnirtung, Lake Harbour, and Iqaluit (Fig. 1). At all of those locations, sites were chosen that had slight to moderate south-to-southwest-facing slopes and were at an elevation of less than 100 m a.s.l. Such sites appeared to be the most favourable for mesic tundra and usually had a continuous vegetation cover.

Analysis of the quadrat data included calculations of dominance and diversity from density. Dominance is defined by Simpson's index of dominance concentration (C),

$$C = \Sigma p_i^2$$

where the sum is over the number of species and p is the proportion of cell area represented by the ith species. Dominance ranges from 0 to 1. Diversity was calculated using the Shannon-Wiener function (H),

$$H = - \Sigma(p_i)(\log_2 p_i)$$

where the sum is as before and p_i is the proportion of the total sample belonging to the ith species (Krebs, 1994). The diversity index increases as the number of species increases or as their abundances become more similar.

Remote Sensing

Multispectral imagery of arctic surfaces has been demonstrated to be useful in distinguishing various land-cover types (Ferguson, 1991) as well as potentially providing the basis for quantitative estimates of plant biomass (Hope et al., 1993). Mapping and classification of surface cover from remotely sensed data such as satellite imagery is best accomplished using ground truth surveys that are synchronous with the collection of the satellite image. This was not possible in the present study, as the decision to use satellite data to map the extent of the various vegetation-landscape formations near Burwash Bay followed the 1986 field season, when most of the vegetation surveys had been completed. A Landsat Thematic Mapper (TM) image for 5 July 1990 was obtained for a 10 000 km^2 area centred southeast of Burwash Bay. To exclude areas with patchy cloud and to remain in reasonable proximity to areas of ground surveys, a subscene covering 6840 km^2 was extracted. Two complementary techniques were used to assess the vegetation cover: the normalized difference vegetation index and a supervised multispectral classification.

The normalized difference vegetation index (NDVI) makes use of the strong absorption and reflectance of live plant leaves in the red and near-infrared bands respectively. Higher NDVI values correspond to greater plant productivity. The NDVI was applied using TM band 3 (0.63–0.69 μm) and TM band 4 (0.76–0.90 μm) in the equation:

$$NDVI = \frac{R_{TM4} - R_{TM3}}{R_{TM4} + R_{TM3}}$$

where R_{TM3} and R_{TM4} are the reflected irradiances in the red and near-infrared bands, respectively (Avery and Berlin, 1992).

While the NDVI gives an indication of the spatial distribution of relative vegetation production, it provides no direct information about the kind of vegetation. For this purpose, a supervised classification of the same TM image was carried out using 1:60 000 aerial photographs from the National Air Photo Library, ground photography, and field notes to designate test areas. A sixfold descriptor was devised, which incorporates moisture (wet, seasonally moist to dry, dry); amount of cover (continuous to patchy, patchy to barren); dominant growth form (grass/sedge, low shrub or heath, lichen/moss/herbs); bedrock (limestone, granite-gneiss); sediments (marine/lacustrine, till); and elevation (above or below marine limit). The training set consisted of 126 polygons identified on the aerial photographs and outlined on transparent overlays. The overlays were georeferenced and matched to the UTM map projection corresponding to that of the Landsat image. As in the NDVI analysis, a mask was used to exclude areas of water (19% of the scene). The resulting classes were grouped into generalized vegetation-landscape types defined in the vegetation surveys as the basis for the supervised classification, which was checked against areas of known cover type outside the training set.

Modern Pollen

Pollen rain at a site provides an indication of the taxonomic composition and relative abundances of wind-pollinated taxa in the local and regional vegetation (e.g., Elliott-Fisk et al., 1982), while fossil pollen assemblages in a stratigraphic context are evidence of past vegetation and, assuming no significant temporal change in vegetation responses to climate, of past climate. The proportion of *Betula* pollen is an indicator of the presence or absence of dwarf birch in an area, and therefore of whether or not low arctic conditions prevail (Andrews et al., 1980). In a study of pollen rain samples conducted well within the low arctic zone in the Frobisher Bay area, Jacobs and others (1985) found that *Betula* pollen percentages averaged 15% in areas of shrub tundra where birch was present and less than 5% in herb tundra areas without birch. Applying the same technique in the Nettilling Lake study area, we collected moss polsters for palynological analysis. Areas sampled included both sides of Burwash Bay as well as the northwest side of Nettilling Lake. The samples were sealed in plastic bags at the time of collection, and the pollen was extracted and analyzed soon after returning from the field, using standard methods (Faegri and Iversen, 1975) with counts based on 300 grains.

Pollen Stratigraphy

In order to assess the past pollen record for the study area, lake sediment samples were taken in a sheltered inlet on the east side of Burwash Bay (Fig. 2). The inlet is fed by a relatively small (10 km^2) drainage basin where dwarf birch was found and which seemed to be representative of low arctic terrain in the granite-gneiss bedrock area. A Livingstone corer was used to take two replicate 1 m long sediment cores in 3.8 m water depth at the centre of the inlet. Core barrels were sealed and returned to the laboratory for analysis. The core barrels were x-rayed before extraction to ensure that the sediments were not distorted. The cores were extruded, and volumetric samples were taken. The samples were analyzed for pollen at 5 cm intervals, with pollen counts based on 300 grains per sample. Bulk samples of organic sediment were taken from the core for radiocarbon dating.

RESULTS

Climatology

The climate station at Burwash Bay operated well from 1987 to 1989, but it experienced problems thereafter and was removed in July 1991. Equipment failure resulted in loss of most of the 1987–88 records for Amadjuak Lake. Otherwise, the equipment performed reliably from July 1988 until it was removed in July 1995. For purposes of this study, Amadjuak Lake, with the longer of the two records, is considered to be the representative station for the interior lowlands. Observations of the main climatic elements are summarized for the 1988 to 1995 period in Table 1, while winds are shown in Figure 3. Total solar radiation received on a horizontal surface is a key climatic element because of its central role in the surface energy balance. The average daily solar flux density is given in Table 1, along with the average transmittance, which is the (dimensionless) ratio of the measured radiation to the flux on a horizontal surface above the atmosphere, calculated according to the method of Peixoto and Oort (1992).

The 1988–95 July mean temperature of 9.1˚C is higher than the long-term July average for any permanent climate station in Baffin Island. Examination of the daily series showed that, on average, the temperature rose above 0˚C around 1 June and above 5˚C about 26 June. The warmest period, with temperatures remaining near 9˚C, was from 1 July to 15 August. The temperature fell below 5˚C on 31 August and below 0˚C on 25 September. A conventional measure of the growing season climate, cumulative degree-days above 5˚C, averaged 195 for Amadjuak Lake, and the length of the growing season, in terms of the same base, was 66 days. The ground temperature record for the well-drained instrument site showed that thawing to 20 cm depth occurred by mid-June.

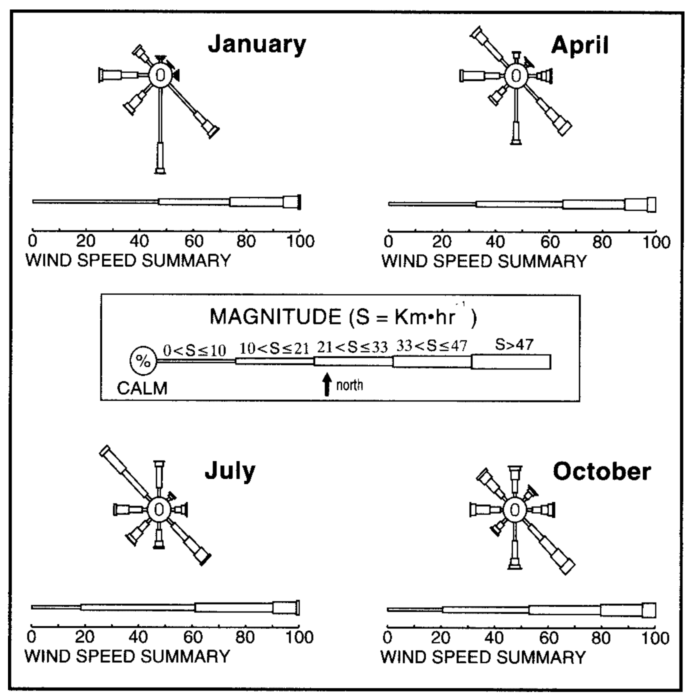

FIG. 3. Average wind speed and direction at Amadjuak Lake for the 1988–95 period. Frequencies in each direction conform to the percentage scale below the diagrams. The overall frequencies by magnitude are shown above the scale. Magnitudes (km h^{-1}) are shown by the shaft width, according to the key in the middle of the figure.

TABLE 1. Amadjuak Lake climate autostation data summary, July 1988 – July 1995.

Month	Solar Flux MJ m² d⁻¹	Trans %	Tmax ˚C	Tmin ˚C	Tavg ˚C	Deg-d >0˚C	Deg-d >5˚C	Deg-d <0˚C	T (-0.1m) ˚C	T (-0.2m) ˚C	RH %	Precipitation mm
Jan	0.8	87	-26.9	-35.9	-31.4	0	0	974	-25.9	-22.0	74	3
Feb	3.7	95	-29.3	-38.4	-33.8	0	0	952	-28.6	-25.3	72	3
Mar	9.6	86	-21.9	-33.4	-27.6	0	0	857	-26.4	-24.9	75	24
Apr	17.1	75	-10.2	-23.1	-16.6	4	0	501	-16.9	-18.7	82	13
May	22.5	66	-1.6	-9.4	-5.5	16	0	183	-4.7	-8.5	88	13
Jun	21.1	52	5.9	0.4	3.1	99	12	9	2.7	0.1	89	22
Jul	17.6	45	12.6	5.5	9.1	231	105	0	7.0	4.8	82	42
Aug	12.2	40	10.2	4.3	7.3	216	71	0	6.7	6.2	88	97
Sep	6.5	33	4.1	0.2	2.2	76	6	12	3.5	4.9	92	89
Oct	3.4	36	-2.3	-7.6	-4.9	5	0	157	-0.5	2.6	93	46
Nov	1.1	34	-11.7	-20.1	-15.9	0	0	477	-10.0	-5.6	87	28
Dec	0.3	50	-21.9	-31.3	-26.6	0	0	824	-20.2	-15.8	79	7
Annual[1]	9.7	58	-7.7	-15.7	-11.7	647	195	4945	-9.4	-8.5	83.4	388

[1] Differences between annual totals and sums of monthly values are due to rounding of the latter values.

Mean daily relative humidity (RH) (Table 1) remained high throughout the summer months, averaging 86% for the period June–August. However, between 10 and 16 hours local time, the average RH was lower, with one-fifth of observations below 75%, indicating a moderately high potential evapotranspiration rate for the growing season. Annual precipitation for the 7-year period ranged from 317 to 444 mm. The record shows a late summer–early autumn maximum. Although the instrument does not allow separation of rain from snow, the July and August precipitation of about 140 mm, representing 36% of the annual total, is assumed to be effective growing season rainfall. Seasonal wind records at Amadjuak Lake (Fig. 3) show the most frequent and strongest winds to be from the northwest and, secondarily, the southeast.

Temperature and precipitation were compared between Amadjuak Lake and the nearest permanent station, Iqaluit, for the 1988–95 period. Mean daily temperatures at Amadjuak Lake were 2 to 3˚C lower in winter than at Iqaluit and about 1˚C higher in summer. Total annual precipitation at Amadjuak Lake averaged 388 mm (Table 1). This amounted to 92% of the annual average amount recorded at Iqaluit for the same period, but the Amadjuak Lake area tended to be slightly wetter than Iqaluit in late summer and early autumn.

Following climatological practice, daily differences for temperature and ratios for degree-days and precipitation were calculated between Amadjuak Lake and Iqaluit to produce empirical coefficients relating the two locations. These relationships can be applied to any particular period as well as to long-term averages. This has been done for the 1961–90 climatological reference (or "normals") period, using the normals for Iqaluit (Atmospheric Environment Service, 1992b) (Fig. 4). Standard errors for all monthly temperature estimates were below 1˚C. Monthly precipitation totals were poorly correlated between the two stations, however the general seasonal trend could be used against the observed values at Amadjuak Lake to produce the estimate of long-term means shown in Figure 4.

Vegetation Studies

The combined surveys at Burwash Bay yielded 118 vascular plant species. Among these are 10 species from a total of 63 shown in distribution maps by Porsild (1964) and Porsild and Cody (1980) to be confined to the low arctic bioclimatic zone in the eastern Canadian Arctic: *Arabis alpina* L., *Betula glandulosa* Michx., *Deschampsia caespitosa* (L.) Bernh., *Epilobium angustifolium* L., *Erigeron humilus* Graham, *Loiseleuria procumbens* L., *Pedicularis lapponica* (L.) Desv., *Potentilla nivea* L., *Poa alpina* L., and *Vaccinium vitis-idaea* L. Our reconnaissance surveys on the north and west sides of Nettilling Lake and on the south and east sides of Amadjuak Lake failed to detect *Betula glandulosa* there or to add to the list of species. The results of the quadrat analysis for the Burwash Bay site and the comparison sites are shown in Table 2. While there is a fairly even representation of different taxa (low dominance) and a moderate diversity at these similar sites across the low arctic zone of Baffin Island, diversity index values are generally lower at Burwash Bay and Pangnirtung, sites at the northern low arctic limit, compared with the more southerly sites at Lake Harbour and Iqaluit.

From the field observations, four distinct vegetation-landscape units were identified in the Nettilling–Amadjuak study area:

1) Wet sedge-meadows, generally in marine or lacustrine sediments and characterized by *Carex* spp. and *Eriophorum* spp.;
2) Low shrub heath in areas of granite-gneiss bedrock, with *Salix arctica*, *Cassiope tetragona*, *Betula glandulosa*, *Vaccinium vitis-ideae*, *Ledum palustre*, and other heath plants, and numerous herbs, grasses, and mosses;
3) Semivegetated granite-gneiss terrain, often with abundant till or till veneer, with species such as *Salix herbacea*, *Saxifraga tricuspidata*, *Luzula confusa*, *Silene acaulis*, and abundant lichens; and
4) Polar semidesert limestone barrens with *Salix lanata*, *Saxifraga oppositifolia*, and *Leucanthemum integrifolium*.

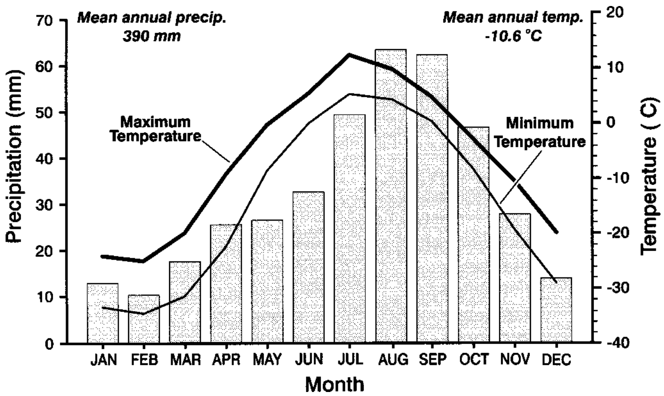

FIG. 4. Climograph showing estimated 1961–90 temperature and precipitation averages for Amadjuak Lake, based on a comparison with the Iqaluit record.

TABLE 2. Plant dominance and diversity indices for low arctic sites on Baffin Island (see text for explanation).

Location	Number of Sample Grids	Dominance	Diversity	Elements
Nettilling Lake	90	0.16	2.93	16
Pangnirtung	90	0.19	2.65	13
Lake Harbour	90	0.14	3.34	23
Iqaluit				
Site 1	44	0.11	3.45	26
Site 2	99	0.15	3.28	21
Site 3	90	0.21	2.87	23

Remote Sensing

NDVI values were calculated for each pixel of the TM image subscene. These were grouped into three classes, centred approximately on the median value in terms of area covered (Table 3). These classes were mapped as shown in Figure 5, with a mask imposed to exclude areas of water (amounting to 19% of the total area). The distribution of the NDVI classes with reference to elevation showed that 60% of the scene pixels in the highest NDVI category were below the 100 m contour, which approximates the marine limit. Most of these pixels are clustered in proximity to Burwash Bay and southward from it (Fig. 5). A second area, also below the marine limit, is in the northeast corner of the subscene.

The results of the supervised classification are shown in Table 4. It was successful in placing 5237 km^2 or 95% of the land area into the four categories, with 46% of that in the continuous vegetation (tundra) categories. About 15% of the total area was classified as "shrub-heath tundra." The relationship of vegetation class to elevation showed 51% of the area under 100 m as tundra, while 68% of the patchy to barren pixels were above 100 m. The area left unclassified (5%) is mainly associated with locations that were not covered in the field surveys and aerial photographs. Mapping of the vegetation classes (not shown), while consistent with the map of NDVI classes (Fig. 5), did not reveal the distinct patterns expected from the field observations. In particular, extensive wet sedge meadows south and west of Burwash Bay below the marine limit did not show up strongly. At the same time, some large patches in that same class were mapped in limestone terrain above the marine limit where such vegetation is not expected, although ground truth is not available to confirm this.

TABLE 3. Normalized difference vegetation index (NDVI) class area (km^2) in relation to 100 m a.s.l. elevation contour based on analysis of the Landsat TM subscene shown in Figure 5.

NDVI class	Elevation		
	Below 100 m	Above 100 m	Total
0 – 0.19	918 (37)[a]	1533 (63)[a]	2451 (44)[b]
0.20 – 0.29	842 (40)	1256 (60)	2098 (38)
0.30 – 1.00	590 (60)	399 (40)	989 (18)
Totals	2350	3188	5538

[a] As % of NDVI Class
[b] As % of total land area

It is likely that on the 5 July 1990 date of the Landsat image, green-up of the tundra was not sufficiently advanced to allow full expression of vegetation differences in the multispectral signature. This was confirmed by examination of digital global vegetation index maps prepared by Gallo (1992) for the 1985–91 period. These maps, derived from infrared and near-infrared imagery from the NOAA satellite series, consist of biweekly and monthly means of daily NDVI values for cloud-free areas. Compared with Landsat TM, the spatial resolution of this product is very coarse, about 10 km at 60° N latitude, but the data are inexpensive and may be examined as a time series. Inspection of these images for the study area revealed that high NDVI values appear first in early June in the coastal lowlands adjacent to Foxe Basin (Fig. 1). For the area between Nettilling and Amadjuak Lakes, there was a two- to fourfold increase in the number of area elements with positive NDVI values between the last week of June and the second week of July, while the median NDVI value for all elements increased by a factor of three. The increase thereafter was small, with median NDVI values starting to decline by mid-August, consistent with our observations.

Modern Pollen

A total of 26 moss polsters were collected from the vicinity of Burwash Bay and along the west side of Nettilling Lake. A full taxonomic analysis of the pollen composition of the samples was done, and the resulting pollen spectra were examined in relation to the percentage of *Betula* and Ericales pollen, representative of the low shrub heath. The overall results showed *Betula* in the range 0.3% to 7.9% (mean = 2.96%, SD = 2.04%), except for one sample with an extreme value of 30.1%, which was noted but excluded from the summary statistics. Ericales ranged from 0.7% to 74.1% (mean = 24.7%, SD = 20.35%). Samples were grouped according to whether they had been collected in the limestone

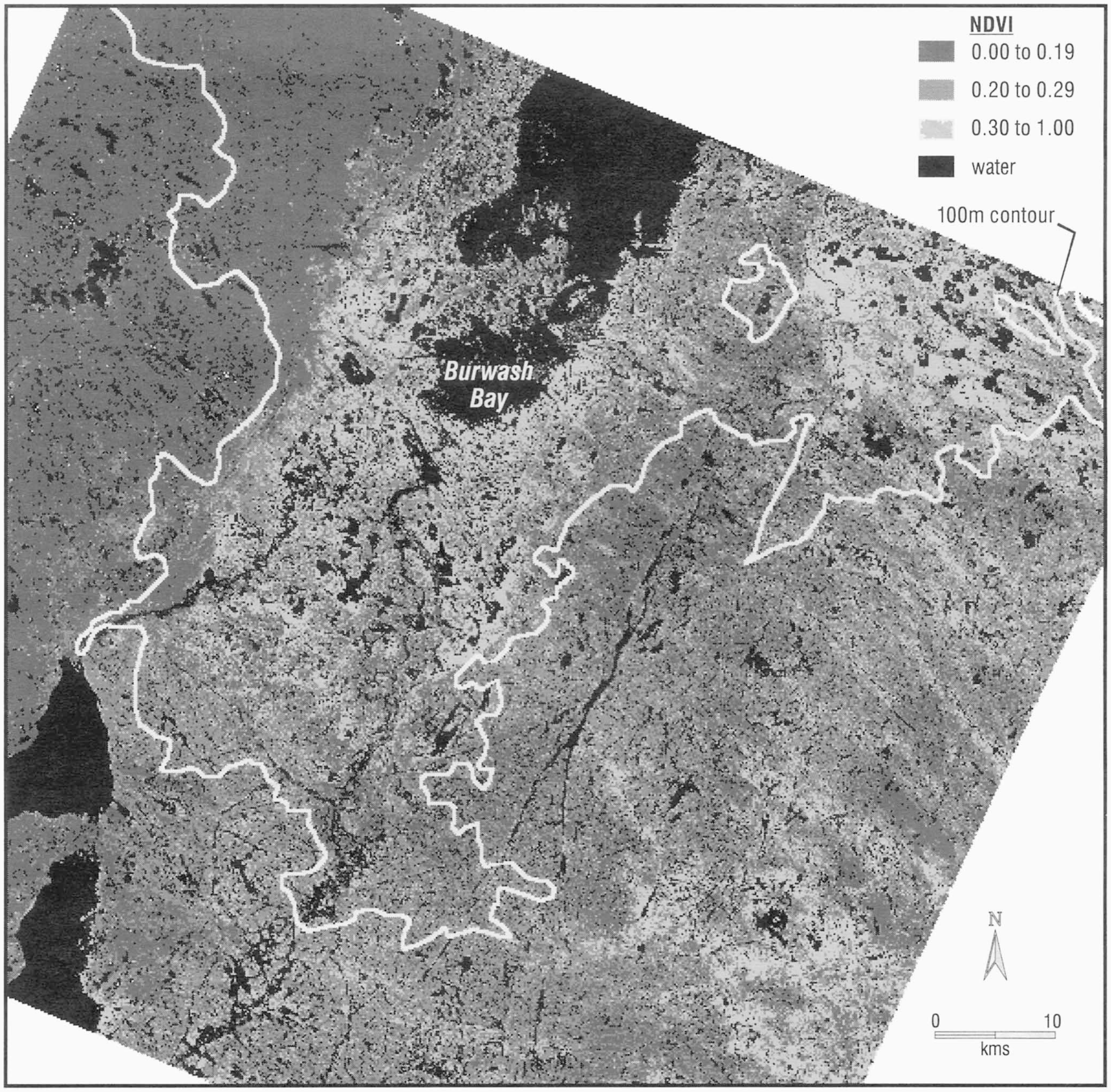

FIG. 5. Threefold classification of the normalized difference vegetation index (NDVI) from a Landsat TM subscene centered at 65.5˚N, 71.05˚W. Higher NDVI values (brighter areas) correspond to areas of densest live vegetation cover.

bedrock area on the west side of the lake or from the granite-gneiss zone on the south and east, where the low shrub heath was found to occur. A Mann-Whitney U test was applied to determine whether the groups were significantly different in terms of Ericales, *Betula*, *Salix*, and *Saxifraga oppositifolia*, the last two considered mild alkaliphiles. The results of the comparison, which tests the hypothesis that the two groups contain samples from the same population, indicate a highly significant difference ($p < 0.01$) in pollen percentages for Ericales, *Betula* and *Salix* between the two terrain types (Table 5).

Pollen Stratigraphy

Radiocarbon dates of 2825 ± 230 (S-2879) and 4290 ± 315 (S-2878) were obtained on gyttja at core levels of 35 and 85 cm, respectively. Extrapolation placed the base of the core at around 4750 B.P., indicating that it represents most of the lacustrine phase of Burwash Bay. The resulting pollen diagram (Fig. 6) does not show any distinct zonation, but rather a gradual trend over most of the period. From the percentages of *Salix* and *Betula* pollen, shrub tundra taxa seem to have been well established by the beginning of the record. *Betula* appears through most of the record in percentages higher than in the modern pollen rain, reaching a maximum of 12% about 3500 B.P. and decreasing thereafter. *Salix* pollen shows a similar decline, with a slight recovery in the present period. Mosimann's multinomial test (Birks and Gordon, 1985) indicated that the declining trend in *Salix* is statistically significant ($p < 0.05$), but that of *Betula* is not. Corresponding to the decline in shrub taxa is an increase in the percentage of sedge. A lake sediment surface sample taken from near the coring site showed 3.4% *Betula*, which is close to the mean value for modern pollen rain within the areas of low shrub tundra (Table 5).

TABLE 4. Results of supervised classification of Landsat TM image (Fig. 5) showing area (km^2) of vegetation-landscape classes with respect to 100 m a.s.l. elevation contour.

Vegetation class	Elevation		Total
	Below 100 m	Above 100 m	
Wet sedge tundra	777 (48)[a]	844 (52)[a]	1621 (31)[b]
Shrub-heath tundra	336 (43)	449 (57)	785 (15)
Semivegetated granite-gneiss	456 (51)	433 (49)	889 (17)
Limestone barrens	626 (32)	1316 (68)	1942 (37)
Total	2195	3042	5237

[a] As % of vegetation class
[b] As % of classified land area

DISCUSSION AND CONCLUSIONS

This study has shown the interior lowlands of southern Baffin Island to be distinctly low arctic in bioclimatic terms. The climatology of this region confirms earlier suppositions of a warm summer climate, with a 72-day growing season and generally adequate moisture. The late summer–early winter precipitation peak reflects the importance of the large lakes and seasonally open waters of Foxe Basin as moisture sources. Freeze-up results in a more continental winter climate, with a mean February temperature of -35°C. The area contains a small but significant proportion of plant species characteristic of the low arctic bioclimatic zone. Species distribution

TABLE 5. Modern pollen percentages from polsters collected within and outside the low shrub tundra zone west and south of Burwash Bay. Probabilities refer to the results of the Mann-Whitney U test (see text).

Pollen taxa	Within			Outside			p (one-tailed)
	mean	SD	n	mean	SD	n	
Ericales	33.6	20.6	14	13.4	13.8	11	0.008
Betula	3.8	2.3	14	1.9	0.9	11	0.001
Salix	6.5	5.9	14	16.4	10.6	11	0.009

maps in Porsild and Cody (1980) show a total of 189 vascular species reported in Baffin Island. With 62% of those species recognized in the Nettilling Lake collections, the area is seen to be relatively rich and diverse in the regional context. According to those maps, our findings of *Betula glandulosa* L., and *Loiseleuria procumbens* (L.) Desv. at Burwash Bay represent a northwesterly extension of their distributions in Baffin Island.

Remote sensing has revealed that at least half of the area around the south end of Nettilling Lake below 100 m a.s.l. is in continuous vegetation, of which low shrub tundra and tundra heath form a significant part. Our field experience suggests that these proportions are an underestimate. The coarser NOAA satellite data indicated that a mid- to late July Landsat image would provide a better reflection of the vegetation cover than did the early July image that was available for this study.

The regional vegetation, as a northern outlier of low arctic tundra in the eastern Canadian Arctic, is what would be

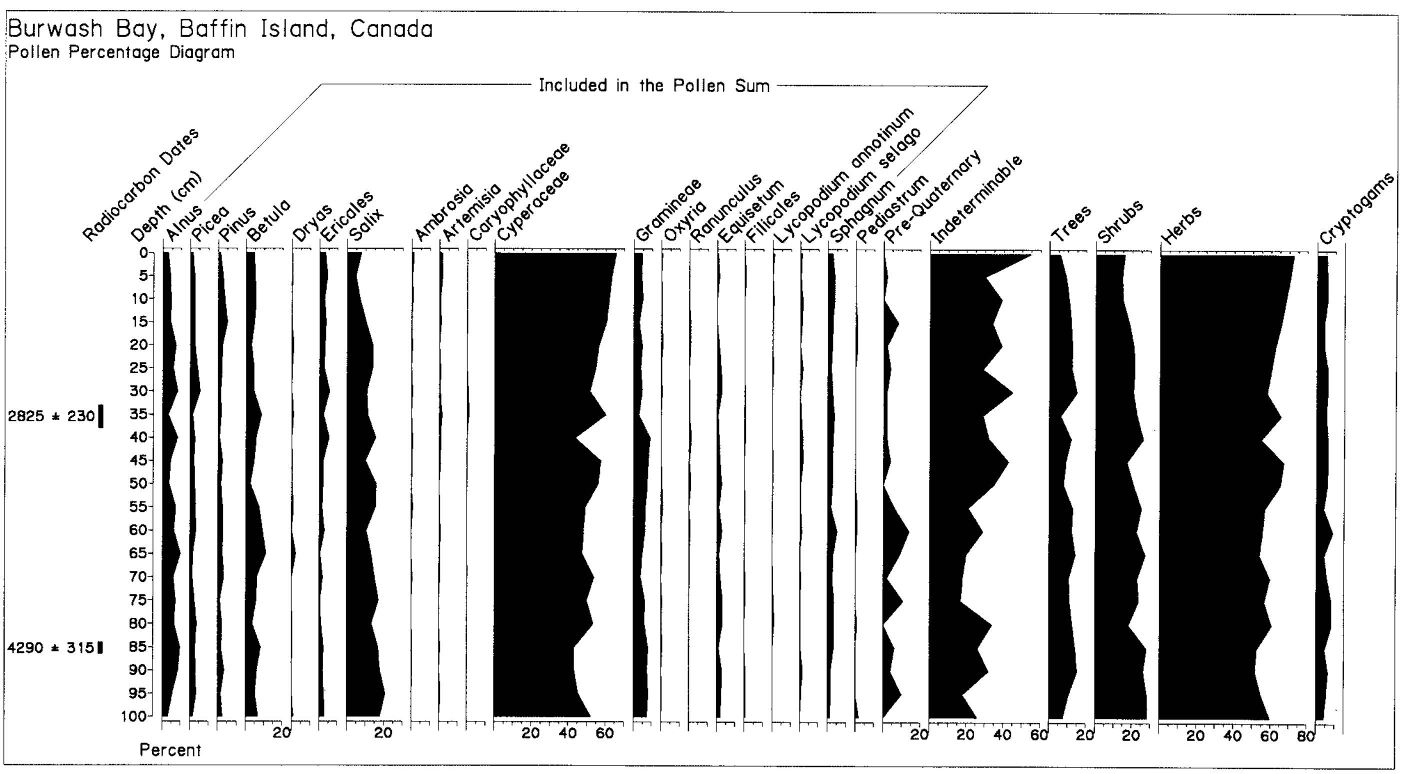

FIG. 6. Pollen percentage diagram for the lake sediment core taken from the inlet shown in Figure 2. Percentages refer to the sum of those taxa within the bracket labeled "included in pollen sum." Dates (radiocarbon years B.P.) are indicated by the bars on the left side of the diagram.

expected from bioclimatic relationships established elsewhere in the Arctic. Young's index of summer warmth, the sum of monthly mean temperatures for all months where T > 0˚C (Young, 1971), is 22 for the Amadjuak Lake record, corresponding to Young's Zone 4 (low arctic). According to Young (1971), Zone 4 predicts the presence of *Betula glandulosa*, which we have confirmed at Burwash Bay. On the other hand, an empirical relationship developed by Rannie (1986) between July temperature and numbers of vascular plants reported at arctic sites predicts about 190 species from the Amadjuak Lake record, compared with the 118 thus far observed.

Our results indicate that there is a decline in vascular plant diversity northward across the low arctic bioclimatic zone in Baffin Island (Table 2). This contrasts with the conclusion reached by Larsen (1989), who presented Shannon-Weiner index values in the range of 1.98 to 3.65 for 73 low arctic sites between 60˚N and 62˚N on the Canadian mainland west of Hudson Bay, but found no latitudinal trend. He concluded that the assumption of declining diversity with increasing latitude may not apply within the low arctic bioclimatic zone. A direct comparison between the two sets of results is not possible, because different community types were considered and fewer locations (as opposed to sample sites) were considered in our case. A larger sample would be required to resolve the question for Baffin Island.

The relationship between modern *Betula* pollen percentages and the presence of dwarf birch in the Burwash Bay area is problematic. Based on relationships found in the Frobisher Bay area (Jacobs et al., 1985), less than 5% *Betula* in the pollen rain should predict an absence of *Betula glandulosa* in the area. In studies involving comparison of *Betula glandulosa* populations near Iqaluit and near Kuujjuaq, in northern Quebec, Weis and Hermanutz (1988) found that the Baffin Island population produced less than 0.5% viable seeds, compared with 70% at Kuujjuaq, and was found to propagate almost exclusively by vegetative layering rather than by sexual reproduction (Hermanutz et al., 1989). The Baffin Island population produced 15% to 30% less pollen, and the pollen rain density in proximity to the Baffin Island stands was less than 10% of that observed in the mainland population (Weis and Hermanutz, 1993). On this basis, it is expected that a dwarf birch population at Nettilling Lake, representing the northern limit of the Baffin Island distribution, would share the reproductive characteristics of the Iqaluit population, with possibly a further reduced reproductive capability.

The fact that dwarf birch is present now at Nettilling Lake, albeit with a relatively low pollen rain, and that the percentage of *Betula* pollen increases with depth (age) in the lake sediments, suggests that birch has been present in the area over most of the last 4000 years. This would be consistent with the regional history described by Williams et al. (1995) of a rapid warming in Baffin Island ca. 6000 B.P., with an expansion of *Betula* showing in the pollen record, and a reversal of these conditions becoming well under way by 3000 B.P. Persistence of *Betula* and therefore elements of a low arctic vegetation association through this period indicates a terrestrial bioclimatic system that is relatively stable under regional variations of climate. It is likely, therefore, that this inland region was as important to the terrestrial biological productivity of southern Baffin Island in the past as it is today.

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