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Regional Congruence of Vegetation and Summer Climate Patterns in the Queen Elizabeth Islands, Northwest Territories, Canada

SYLVIA A. EDLUND[1] and BEA TAYLOR ALT[1]

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ABSTRACT. In the Queen Elizabeth Islands, regional distributions of vegetation and many summer climate patterns show similar, distinctive S-shaped patterns, a response to the interaction between regional topography and persistent northwesterly flow from the central Arctic Ocean. The cool and cloudy central polar pack ice climate bulges almost unimpeded into the low-lying islands of the northwest and north-central sector. This region has the least vascular plant diversity and is dominated almost entirely by herbaceous species. The mountains of Axel Heiberg and Ellesmere islands create a barrier that effectively shelters an intermontane region from both the central Arctic Ocean climate and travelling cyclonic systems. In this large intermontane zone regional minimums of cloud cover and maximums of temperatures and melt season duration are found. This area contains the most dense and diverse vascular plant assemblages. Woody species and sedges dominate, and many species with more southerly limits occur as disjuncts. The plateaus and highlands in the southern islands modify the central Arctic Ocean climate sufficiently to produce an intermediate climate. Woody species and sedges also dominate this area; however, the density and diversity are less than that of the intermontane area.

Several phytogeographic limits occur in the Queen Elizabeth Islands, including the northern limits of woody plants and sedges, and the northern limits of the dominance of woody plants and sedges. These regional boundaries roughly coincide with regional mean July isotherms of 3 and 4°C respectively.

Key words: Arctic, High Arctic, arctic vegetation, Canada, climate, summer climate, bioclimatic zones, Queen Elizabeth Islands, phytogeographical boundaries

RÉSUMÉ. Dans les îles de la Reine-Elizabeth, les distributions régionales de la végétation et de nombreux schémas climatiques d'été montrent des motifs particuliers semblables en forme de S, en réponse à l'interaction entre la topographie régionale et les courants constants du nord-ouest venant du centre de l'océan Arctique. Le climat du pack polaire central frais et nuageux pénètre pratiquement sans obstacle dans les îles basses du secteur nord-ouest et centre-nord. Cette région a le moins de variété de plantes vasculaires et elle est dominée presque entièrement par des espèces herbacées. Les montagnes de Axel Heiberg et des îles Ellesmere créent une barrière qui abrite de façon efficace une région intermontagneuse, à la fois du climat du centre de l'océan Arctique et des systèmes cycloniques qui passent au-dessus. Dans cette vaste zone intermontagneuse, on trouve des minimums régionaux de couverture nuageuse et des maximums de température et de durée de la saison de fonte. Cette zone contient les ensembles de plantes vasculaires les plus denses et les plus variés. Les espèces ligneuses et les cypéracées dominent, et de nombreuses espèces que l'on trouve généralement plus au sud, s'y trouvent sous forme d'espèces séparées. Les plateaux et hautes-terres dans les îles du sud modifient suffisamment le climat du centre de l'océan Arctique pour produire un climat intermédiaire. Des espèces ligneuses et des cypéracées dominent aussi dans cette région; cependant, leur densité et leur diversité sont moindres que celles de la zone intermontagneuse.

On trouve plusieurs limites phytogéographiques dans les îles de la Reine-Elizabeth, y compris les limites nordiques des plantes ligneuses et des cypéracées et les limites nordiques de la dominance des plantes ligneuses et des cypéracées. Ces limites régionales coïncident en gros avec les isothermes moyens régionaux de juillet de 3 et 4° respectivement.

Mots clés: Arctique, Extrême-Arctique, végétation arctique, Canada, climat, climat estival, zones bioclimatiques, îles de la Reine-Elizabeth, limites phytogéographiques

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INTRODUCTION

The worldwide distribution of ecosystems has been shown to be dependent on the regional climates (Köppen, 1923; Dansereau, 1957; Holdridge, 1947, 1966). Most bioclimatological studies, however, have been carried out in the tropics, temperate, and boreal regions. Holdridge's classification, while including the Arctic, does not reflect the complexity of factors affecting arctic ecosystems. The Queen Elizabeth Islands (Fig. 1) represent the extreme arctic ecosystem, where most plants are at or near their physiological limits of tolerance. Vegetation, therefore, should be extremely sensitive to variations in climate.

Studies of the regional distribution of vegetation in the Queen Elizabeth Islands have suffered due to the inaccessibility of the region. Since the days of European exploration in the 19th century, floristic data have slowly been compiled (Hooker, 1857; Simmons, 1906, 1913; Polunin, 1940a,b, 1948; Porsild, 1964). Most specimens were collected as an adjunct to other projects by non-botanists, and with little data as to the complete flora or the plant assemblages of a site. None the less, important preliminary observations of the influence of geology on the patterns of vegetation distribution were made (Thorsteinsson, 1958; Tozer and Thorsteinsson, 1964). Since the 1940s, knowledge of arctic ecosystems increased as more detailed floristic and plant community analyses were done around the most easily accessible sites, such as logistics bases at Resolute (Schofield and Cody, 1955; Arkay, 1972), Eureka and Alert (Bruggemann and Calder, 1953). Many recent scientific expeditions included a botanical component, usually site specific or local coverage, particularly in areas of Axel Heiberg and northern Ellesmere Island and other well-vegetated areas (Beschel, 1961, 1962; Brassard and Beschel, 1968; Brassard and Longton, 1970; Waterston and Waterston, 1972; Cody *et al.*, 1976; Parker, 1977, 1978; Parker and Ross, 1976; Powell, 1961; Savile, 1961, 1964, 1971; Mausbacher, 1981; Sheard and Geale, 1983a,b). Long-term intensive vegetation studies were initiated at several well-vegetated sites in the Queen Elizabeth Islands (Fig. 2): Truelove Lowland, Devon Island (Barrett, 1972; Barrett and Teeri, 1973; Bliss, 1977), Alexandra Fiord, Ellesmere Island (Freedman *et al.*, 1983; Svoboda and Freedman, 1981; Bridgland

[1]Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, Canada K1A 0E8

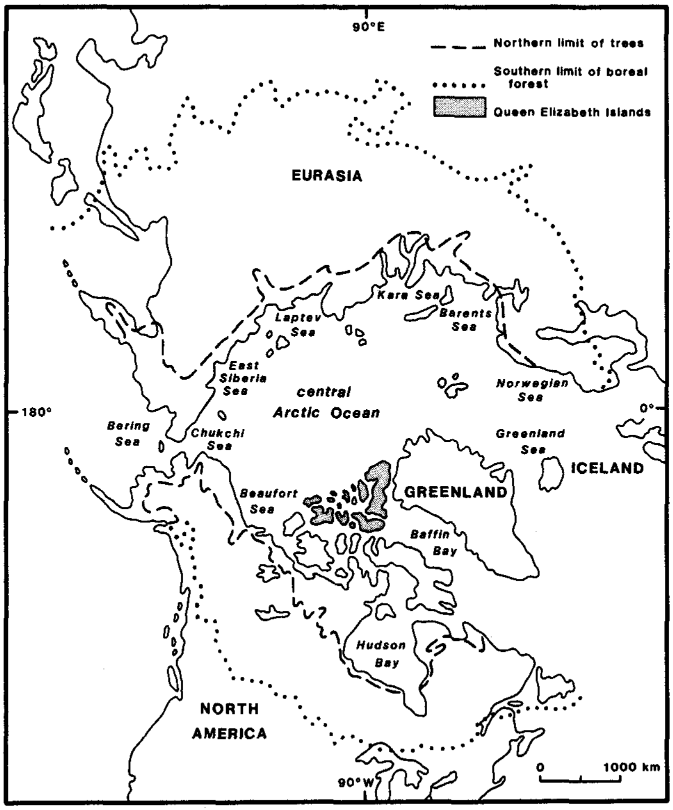

FIG. 1. Circumpolar arctic projection, showing the location of the Queen Elizabeth Islands with reference to the central Polar Ocean (the Polar Ocean minus the peripheral seas; Orvig, 1970), Arctic (north of tree line), and the boreal forest ecosystems between tree line and southern limit of Boreal Forest (Larsen, 1980). Note: Polar Ocean is defined as the Arctic Ocean excluding the Norwegian and Barents Sea (Hare, 1968).

and Gillett, 1984), Sverdrup Pass, Ellesmere Island (Svoboda and Freedman, 1981; Henry *et al.*, 1986), and Lake Hazen, Ellesmere Island (Powell, 1961; Savile, 1964; Soper and Powell, 1983; Gould, 1985), and at poorly vegetated sites, such as Isachsen, Ellef Ringnes Island (Savile, 1961, 1971) and King Christian Island (Bell and Bliss, 1977a,b). Studies at several of these sites are currently ongoing. Between these intensively studied areas, however, there are vast expanses of terrain about which there is little information.

The discovery of oil, gas, and mineral reserves in the region in the late 1960s and early 1970s and proposals to build pipelines to transport resources to southern markets provided the impetus for regional studies, which required inventories of all terrain to be crossed (Barnett *et al.*, 1975; Hardy and Associates Ltd., 1977). This thrust resulted in the production of maps that could be used for environmental impact assessment (Hodgson and Edlund, 1975, 1977, 1978; Edlund, 1980, 1982a,b, 1983c,d, 1987b).

Regional Setting

The Queen Elizabeth Islands (74-83°N; Fig. 2) make up the northern half of the Canadian Arctic Archipelago. This area offers a unique opportunity to investigate arctic plant communities and individual vascular plant species at their northern limits, for the terrain spans a broad range of both latitude and longitude. This contrasts with northern Eurasia, where critical limits of the Arctic are compressed latitudinally into a narrow rim along the continental margin and which includes a few islands in the Arctic Ocean (see Alexandrova, 1970; Aleksandrova, 1980).

The Queen Elizabeth Islands also provide a variety of soil lithologies, which enable a better understanding of the role of soils as an influence on vegetation distribution. Along the northernmost sector the bedrock generally consists of poorly lithified Mesozoic and Cenozoic sediments of the Sverdrup Basin. Most of the southern and eastern islands are composed of Paleozoic carbonates and clastics that are moderately to well lithified. The oldest and most competent bedrock occurs in the southeast, where metamorphic Precambrian rocks form the easternmost rim of Ellesmere and Devon islands (Hodgson, in press).

The highest topography coincides with the most competent bedrock. Mountain systems of eastern Ellesmere Island and adjacent Axel Heiberg Island reach heights greater than 2200 m. Glaciers currently cover roughly 50% of the highland surface of these mountainous islands. The arctic platform carbonates and clastic sediments, which are generally horizontally bedded, form plateaus of 300-600 m a.s.l. along the southern and east-central sectors. The soft sediments of the Sverdrup Lowland (Bostock, 1967), the group of low-lying islands in the north-central and northwest sector, rarely reach elevations greater than 150-200 m a.s.l.

Weathered bedrock is the most common surficial material in the region, for most of the area lies north of the limit of Late Wisconsinan continental glaciation, which was responsible for extensive glacial deposits on the mainland and the islands to the south (Dyke and Prest, 1987). Continental ice encroached only into the southernmost part of the Queen Elizabeth Islands during this glaciation (Hodgson and Vincent, 1984). Local ice caps on the high plateaus and mountainous regions may have expanded somewhat during the Quaternary, but their extent and timing has yet to be determined (Hodgson, in press). Elevated flights of beach ridges ring the coastal regions of all islands as a result of post-glacial marine transgressions. These marine episodes altered the general character of the surficial materials somewhat, by mixing lithologies and incorporating marine deposits. These marine reworked materials may provide a greater range of plant nutrients than the weathered bedrock itself provides.

Soil horizon development on these surficial materials is generally minimal (Foscolos and Kodama, 1981). Soil development on extremely alkaline soils is greatly impeded due to the high carbonate content (Tarnocai, 1976). Poorly vegetated terrain generally does not produce sufficient organic material to alter the surface soil chemistry. Poorly drained soils locally may show a thin, organic-rich mineral horizon. But generally the surface soil chemistry shows only slight modification from the chemistry of the parent material. Some soils are also extremely disturbed by cryoturbation or mass movement.

Previous Subdivisions of Arctic Vegetation

Prior to the availability of such maps, several types of subdivisions of arctic vegetation have appeared in the literature. Polunin (1951, 1960; Energy Mines and Resources, 1973) divides the Arctic into three vegetation regions, Low, Mid, and High Arctic, based on continuity of ground cover and

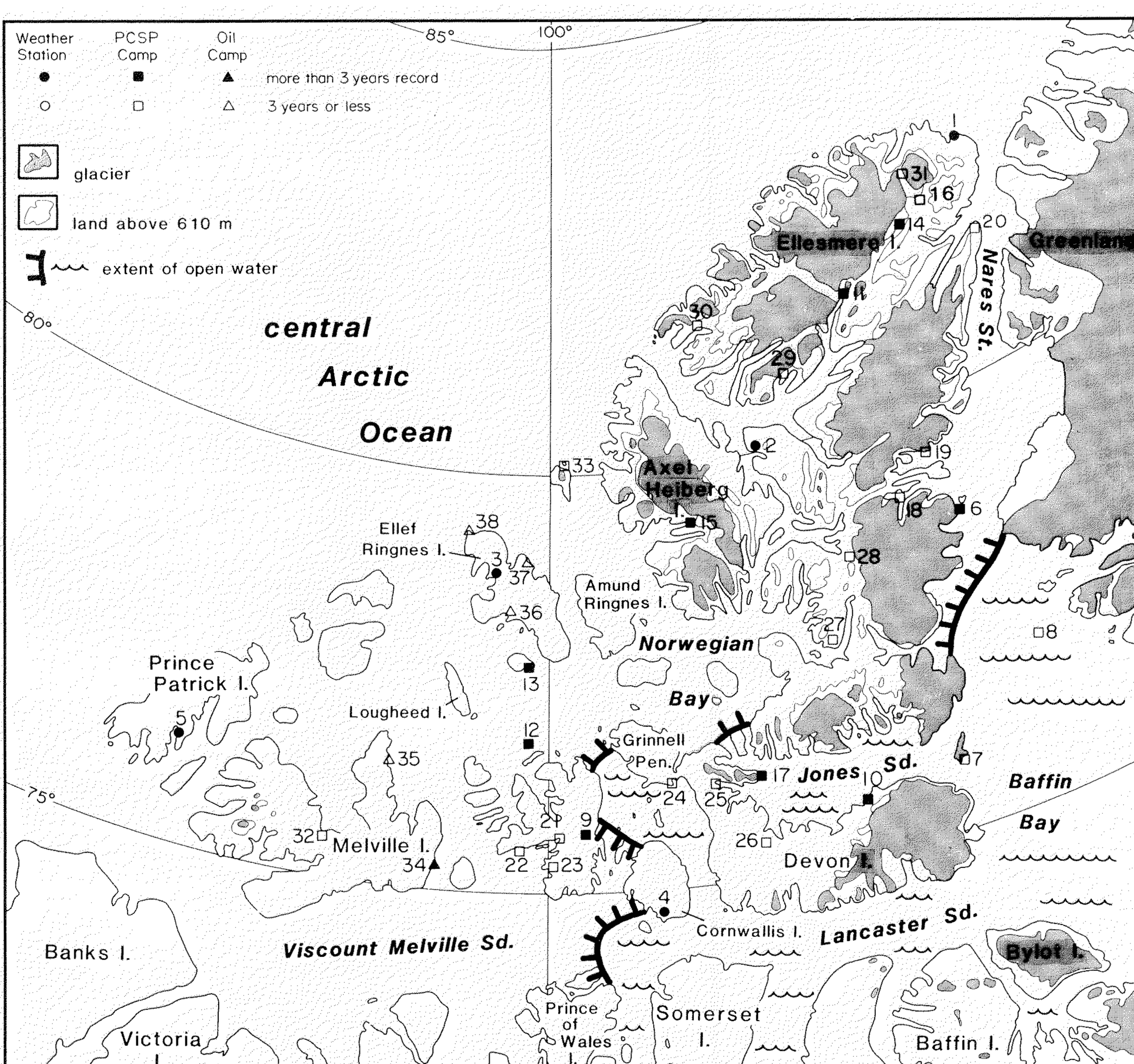

FIG. 2. The Queen Elizabeth Islands, showing the topography, modern glaciers, and the maximum extent of open water in a typical year (Maxwell, 1982). Also shown are: Permanent Weather Stations (AES, 1982, unless otherwise noted): 1. Alert; 2. Eureka; 3. Isachsen; 4. Resolute Bay; 5. Mould Bay. PCSP Supported Short Duration Stations (from PCSP and AES data archives unless otherwise noted): 6. Cape Herschel (Müller *et al.*, 1976); 7. Coburg Island (Müller *et al.*, 1976); 8. Cary Island (Müller *et al.*, 1976); 9. Polar Bear Pass (D. Gill, National Museum of Natural Sciences, pers. comm. 1985); 10. Truelove Inlet (Bliss, 1977); 11. Tanquary Fiord (King, 1981; PCSP records); 12. Seymour Island (D. Gill, pers. comm. 1985); 13. King Christian Island (Addison and Bliss, 1980); 14. Lake Hazen (King, 1981; Jackson, 1959); 15. Expedition Fiord (Ohmura, 1981); 16. Piper Pass; 17. Cape Vera; 18. Alexandra Fiord; 19. Princess Marie Bay; 20. Judge Daly Promontory; 21. Bracebridge Inlet; 22. Bradford Island; 23. Hooker Bay; 24. Porden Point; 25. Eidsbotn Fiord; 26. Haughton River; 27. Baumann Fiord; 28. Strathcona Fiord; 29. Neil Peninsula (King, 1981); 30. Irish Arctic Expedition; 31. Clements Markham Inlet; 32. Nias Point; 33. Meighen North. Oil Industry Camps (from PCSP and AES data archives): 34. Rea Point; 35. Drake Point; 36. Dome Bay; 37. Malloch Dome; 38. Cape Isachsen.

species diversity. The Queen Elizabeth Islands lie entirely within his High Arctic zone, reflecting the generally low percentage of ground cover and low diversity of the region.

Young (1971) presents a comprehensive circumpolar floristic classification, based on species diversity. His zones also reflect the impoverishment of much of the Queen Elizabeth Islands, for most of the region lies within zones 1 and 2, the most impoverished zones, while zone 3 includes parts of Ellesmere Island, where the vegetation is the most diverse and is comparable to floras farther south. Beschel (1969) numerically shows similar floristic trends on an island-wide basis.

Bliss (Babb and Bliss, 1974; Bliss, 1975, 1977; Bliss and Svoboda, 1984; Bliss *et al.*, 1984) divides the Arctic into two major regions based on observations on density of plant cover and implied soil moisture characteristics: Low Arctic, encompassing the continental region and the southeasternmost tip of Baffin Island, and High Arctic, which includes all of the islands in the Arctic Archipelago, Boothia and Melville peninsulas and Wager Plateau. He further subdivides the High Arctic into three types, Polar Desert, Polar Semi-desert and a Complex, which includes Polar Desert, Polar Semi-desert and Sedge meadows (Bliss, 1977). All three High Arctic types occur throughout the Arctic Archipelago, although the aerial extent of the Complex is limited in the Queen Elizabeth Islands.

As Edlund's coverage of regional vegetation mapping increased, regional vegetation patterns emerged that could not be explained by changes in substrate or moisture regimes (Edlund, 1983a), nor were these changes fully covered in the earlier types of vegetation zonation, except in most general terms. For example, the contrast between the generally impoverished flora of the north-central and northwestern Queen Elizabeth Islands and at the same latitude the exceptionally rich flora of the northeast is reflected in Young's zones but is not accurately detailed. A much more detailed distribution of the vascular plant flora and plant communities is now possible.

The favourable summer climate experienced at Eureka and Lake Hazen, Ellesmere Island, though only partially understood, has been well documented (Sim, 1957; Jackson, 1959, 1969; Maxwell, 1980, 1982; Barry and Jackson, 1969). The harsh climate of the northwestern sector has also been described (Alt, 1979; Addison and Bliss, 1980; Maxwell, 1980, 1982). The results of Alt's ongoing atmospheric circulation studies (Alt, 1987) provide a satisfactory explanation for this extreme contrast.

Similarities between vegetation and summer climate patterns were evident once the authors began to compare notes. This paper explores the hypothesis that summer regional climate strongly influences the regional distribution patterns of both vascular plant species and associations.

VEGETATION DISTRIBUTION IN THE QUEEN ELIZABETH ISLANDS

Methods

During ten field seasons in various parts of the Queen Elizabeth Islands, Edlund measured percentage cover of vegetation and divided the assemblages into plant communities at 130 locations, using line transect, quadrat, or pin frame techniques, depending on the relative abundance of vegetation (Wein and Rencz, 1976). Visual surface estimates were made at 685 additional sites. Notes were made on the type of surficial material on which the plants were growing, including its texture, moisture regime, and the parent material. Soil chemistry, including pH, was done at various laboratories, including Terrain Sciences Sedimentology laboratory, Land Resource Research Institute, and Institute for Sedimentary and Petroleum Geology, as well as several commercial laboratories.

Voucher specimens documenting the diversity of vascular plants for each island, as well as specimens representing range extensions, have been incorporated into the national collection at the National Herbarium, where the data for each specimen is computer retrievable. Nomenclature for vascular plant families and species in this paper follows that of Porsild and Cody (1980).

Controls of Vegetation Patterns by Surficial Materials

The physical and chemical properties of arctic soils influence both vascular plant species and plant community distributions in the Queen Elizabeth Islands (Thorsteinsson, 1958; Tozer and Thorsteinsson, 1964; Edlund, 1980, 1986b, in press). Since horizon development for most soils in this region is minimal, vascular plants root directly into soils with physical and chemical properties similar to that of weathered surficial deposits. Thus the chemical composition of the materials provides much of the plant nutrients.

Some materials are inimical to plant life. Soils derived from highly acidic shales (pH 3), such as a facies of Kanguk shale that locally occurs on the Ellef Ringnes, Amund Ringnes, Lougheed and Melville islands, which are devoid of plant nutrients, are unvegetated (Barnett *et al.*, 1975; Hodgson and Edlund, 1978; Edlund, 1980, 1982b, 1983d). Weathered silt and rock fragments derived from the highly alkaline (pH 8.2+) carbonates that cover vast tracts of Bathurst, Cornwallis, and Devon islands, contain excessive calcium and magnesium ions but lack a variety of other plant nutrients and are also unvegetated. On a more local scale, cryoturbation, mudboil activity, and wind deflation or deposition of fine-grained materials also create local situations that are unstable due to their immaturity or instability.

Other soils in the Queen Elizabeth Islands, however, have chemical properties within the range of tolerance of arctic vascular plants. Nonetheless, the degree of alkalinity or acidity greatly influences the distribution of vascular plant species and communities (Fig. 3). Moderately to well-drained weakly alkaline materials (pH 7.4-7.8) are vegetated predominantly by calciphilous species such as *Dryas integrifolia* (arctic avens) and *Saxifraga oppositifolia* (purple saxifrage); other calciphilous species, such as *Lesquerella arctica*, *Parrya arctica*, and *Poa abbreviata* also may be common.

Weakly acidic mesic soils (pH 5.6-6.6) have a different suite of vascular plants. Herbs such as *Luzula confusa*, *Potentilla hyparctica* are common, and the heath species *Cassiope tetragona* occurs sporadically. Some species, such as *Salix arctica* (arctic willow), *Alopecurus alpinus* (foxtail grass), *Draba* species, *Cerastium alpinum*, *Stellaria longipes*, and *Papaver radicatum* (arctic poppy) tolerate both weakly alkaline and weakly acidic conditions (Edlund, 1983a).

Wetlands rarely exhibit extremes of pH, for accumulating organics and a reducing environment modify the pH of the soil surface, generally resulting in soils within the weakly acidic to nearly neutral range (pH 6.6-7.2). Sedges and/or grasses dominate the poorly drained to saturated substrates, with forbs and some woody plants occurring on slightly raised hummocks. Wet, highly alkaline soils with minimal organic accumulation usually lack sedges even in regions where they are dominant.

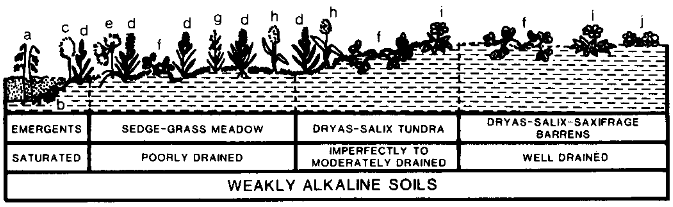

FIG. 3. Catena showing the suites of plant communities on weakly alkaline surficial materials for each broad type of moisture regime in an area that supports prostrate shrub communities on moderately to well-drained soils and sedge meadows on poorly drained soils. Typical species include: a. *Pleuropogon sabinei*; b. *Ranunculus hyperboreus*; c. *Eriophorum scheuchzeri*; d. *Carex aquatilis* var. *stans*; e. *Eriophorum triste*; f. *Salix arctica*; g. *Arctagrostis latifolia*; h. *Alopecurus alpinus*; i. *Dryas integrifolia*; j. *Saxifraga oppositifolia*.

Soil Moisture and Vegetation Patterns

Based on measured precipitation levels in the Queen Elizabeth Islands, the region is classified as a cold Desert (Lotz and Sagar, 1962; Bliss, 1977; Bliss and Svoboda, 1984; Bliss *et al.*, 1984). This does not, however, give an accurate impression of soil moisture availability. Precipitation falling as snow is redistributed by winds into drifts on lee-side slopes and into valleys, while convex surfaces and promontories may have only a thin snow cover or indeed may even be blown free of snow in winter.

Meltwater and summer rainfall are not lost from the arctic ecosystem by percolation, for the entire land area is underlain by permafrost, which blocks percolation below the base of the active layer (10-100 cm deep). Lower slopes and valley bottoms generally receive moisture throughout summer from melting snow drifts and ice lenses within the soils as the active layer deepens. Persistent snow drifts may provide moisture downslope for much of the thaw period.

Hilltops with thin or discontinuous winter snow cover, however, may be extremely dry in summer, for there is no external meltwater source, and precipitation does not wet more than the top few centimetres of soil.

Therefore, the summer moisture regime varies with topographic position and proximity to a moisture source. Even in regions with less than 40 mm of measured annual precipitation, extensive wetlands can develop in lowlands and downslope from permanent snowbeds. Slight changes in moisture regimes result in changes in plant assemblages. For each type of material there is a suite of plant communities that reflects changes in local soil moisture availability (Fig. 3).

Shift in Dominant Species

Island-by-island studies afforded the opportunity to compare vegetation on similar formations in different areas of the Queen Elizabeth Islands (Barnett *et al.*, 1975; Hodgson and Edlund, 1975, 1977, 1978; Edlund, 1980, 1982a,b, 1983c,d, 1987b). Communities on the Christopher shale formation could be studied on Melville, Lougheed, Amund Ringnes, Ellef Ringnes, and Ellesmere islands. In similar fashion, both weakly and highly alkaline soils on Melville, Bathurst, Cornwallis, Cornwall, and Ellesmere islands could be compared. While lists of vascular plants on similar materials from the different islands generally included the same species, the dominance and abundance of species shifted both with regional changes and with changes in elevation (Fig. 4).

Definitive regional patterns of growth form distributions emerge, irrespective of the soil type. The most obvious patterns involve shifts in the dominance, presence, or absence of prostrate and matted woody species on moderately to well-drained soils, such as the shrubs *Salix arctica*, and *Dryas integrifolia* and local occurrences of *Cassiope tetragona*. Similar shifts in dominance, presence, or absence occurs with sedges in wetlands and on seepage slopes (Fig. 4).

The dominant species on moderately to well-drained soils at similar elevation had similar growth forms, although the actual species differed depending on the soil chemistry. For example, along the coast of southern Melville Island weakly alkaline silty till is dominated by woody species, a mixture of *Dryas integrifolia* and *Salix arctica*, while adjacent acidic sandy silt was dominated by *Salix arctica*. In the same region but at 250 m elevations, alkaline till is dominated by *Saxifraga oppositifolia*, a common associate at lower elevations. On acidic soils, *Luzula confusa* and grasses were the dominants. Woody species, if present, were not dominant or even abundant. Shrubs were restricted locally to the warmest and most sheltered locations (Edlund, 1983a, 1986a,b).

Associations in the wetlands also undergo shifts in dominance (Fig. 4). Wetlands in the coastal zone of southern Melville Island were dominated by sedges. At the higher elevations, however, grasses, generally those that are common associates in the coastal lowlands, are now dominant; sedges are rare, most commonly absent.

Similar shifts occur at the regional level as well. Weakly alkaline till of the Fosheim Peninsula, Ellesmere Island, and southern and western Melville Island support dense and diverse *Dryas*- and *Salix*-dominated communities and sedge meadows, while the chemically similar materials on northern Bathurst, northern Cornwallis, northeastern Melville, Cameron, Lougheed, Amund Ringnes, and Ellef Ringnes islands are dominated by *Saxifraga oppositifolia* and a few species of herbs. Shrubs, if present, never dominate. Wetlands of adjacent areas are sparsely vegetated by a few grasses, most commonly *Alopecurus alpinus*; sedges are rare, more frequently absent (Edlund, 1980, 1982a,b, 1983c,d, 1987b, in press).

Vegetation maps prepared for environmental impact assessment proved to be useful in delineating regional patterns. Plant associations were mapped at 1:60 000 scale on air photos and transfered to 1:250 000 scale maps. For this study the maps were reduced to 1:1 000 000 scale to facilitate regional comparisons. Fifteen plant associations were delineated, reflecting broad changes in moisture regimes and soil chemistry. These associations were grouped according to the growth form of the dominant vascular plants. These shifts also paralleled changes in total vascular plant species diversity within the communities.

Vegetation Zonation

Five vegetation zones based on the presence and dominance of key species, such as shrubs and sedges are described (Table 1). Zonal vascular plant diversity is calculated by summing the total floras on all types of materials and moisture regimes

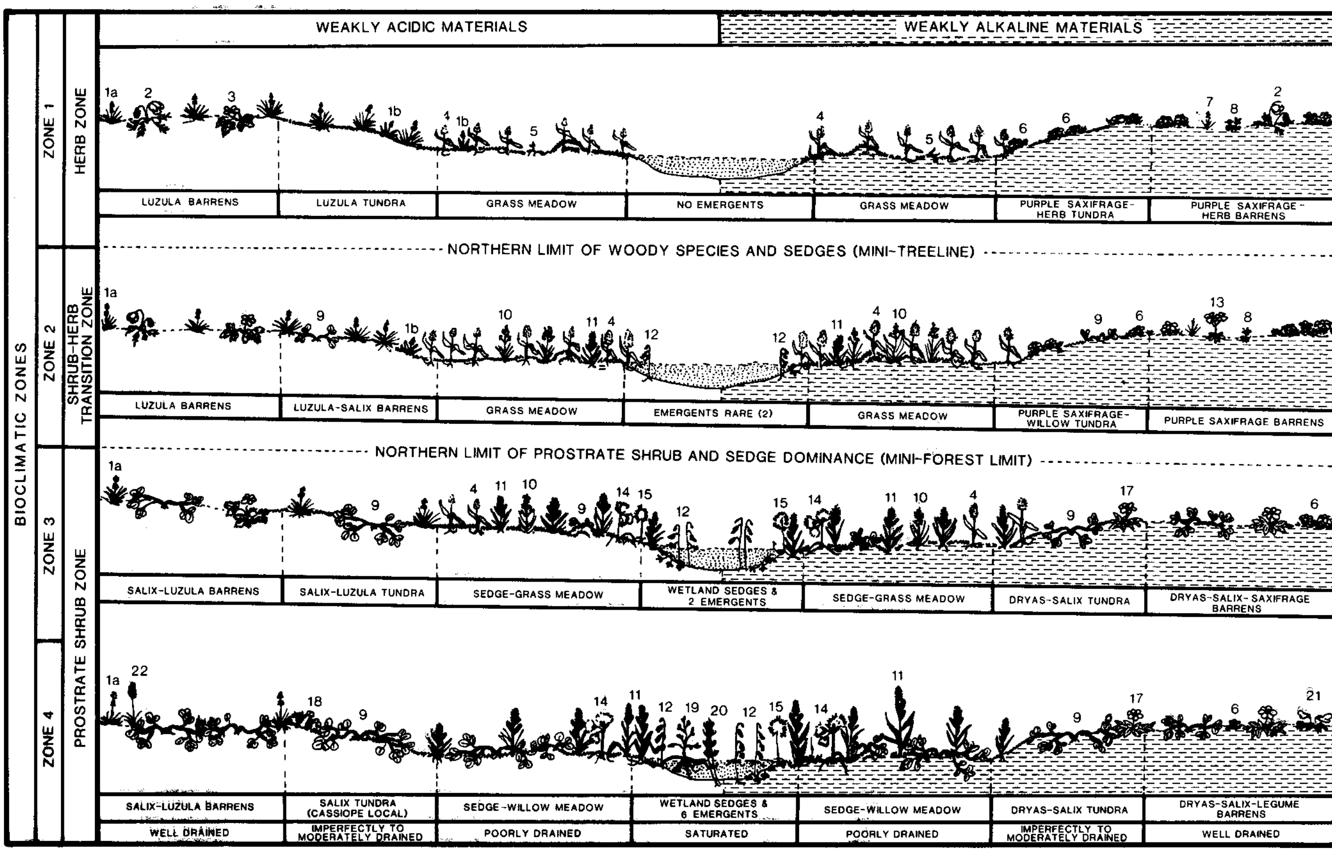

FIG. 4. Catena for each vegetation zone. Species illustrated include: 1a. *Luzula confusa*; 1b. *Luzula nivalis*; 2. *Papaver radicatum*; 3. *Potentilla hyparctica*; 4. *Alopecurus alpinus*; 5. *Phippsia algida*; 6. *Saxifraga oppositifolia*; 7. *Poa abbreviata*; 8. *Draba* sp.; 9. *Salix arctica*; 10. *Dupontia fisheri*; 11. *Carex aquatilis* var. *stans*; 12. *Pleuropogon Sabinei*; 13. *Parrya arctica*; 14. *Eriophorum triste*; 15. *Eriophorum scheuchzeri*; 16. *Ranunculus hyperboreus*; 17. *Dryas integrifolia*; 18. *Cassiope tetragona*; 19. *Arctophila fulva*; 20. *Hippirus vulgaris*.

TABLE 1. Characteristics and diversity of vegetation zones in the Queen Elizabeth Islands

Zone	Name and characteristics	Diversity
0	**Unvegetated** – lacks both cryptogamic and vascular plants, even though the soil chemistry could support plant growth	0
1	**Herb zone** – entirely herbaceous; with no shrubs or sedges	1-35
2	**Herb-shrub transition zone** – herb dominated; shrubs and sedges present but not dominant; wetlands dominated by grasses	35-60
3	**Prostrate shrub zone** – dominated by *Salix arctica* and/or *Dryas integrifolia*; wetlands dominated by sedges	60-100
4	**Enriched prostrate shrub zone** – dominated by shrubs, as in zone 3, but includes more dense and diverse vascular plant flora, such as Ericaceae, Asteraceae, *Epilobium latifolium*, tiny *Salix* species; wetlands are dominated by a variety of sedges	100+

within each vegetation zone. The vegetation zones are named for the dominant growth form of communities on moderately to well-drained soils, although the assemblages for all types of material and moisture regimes were compiled in some detail (Fig. 4). Table 2 elaborates the more common floral components within each zone for a variety of moisture regimes.

When mapped, these zones show a complex pattern, reflecting topographic variation and some latitudinal variation (Fig. 5). To facilitate comparisons on a regional scale the effects of altitude can be ignored, resulting in a regional picture (Fig. 6) that can be viewed as a vegetation potential map, showing the best possible type of vegetation that can be expected if materials had sufficient moisture, if the soils chemistry were not inimical to plants, and if the area were near sea level.

These limits form an S-shaped pattern in the Queen Elizabeth Islands. Some boundaries are nearly superimposed in the mountainous region of northern Ellesmere Island. Woody plants are common as far north as Alert (82°30′N) and are present in the heads of some fiords along the north coast of Ellesmere Island but are absent close to the coast (J. Bednarski, pers. comm. 1987). This transition zone between zones 1 and 3, however, becomes wider in the central, low-lying islands. Both limits protrude southward into the Sverdrup Basin. The regional limit of woody plant dominance occurs as far south as 75°30′N.

The boundary between zones 3 and 2 represents the northernmost limit of woody plant dominance and is in effect the northern arctic equivalent of the northern forest limit. Likewise the boundary between zones 2 and 1 is the northern limit of the presence of woody plants, the northern arctic

TABLE 2. Selected vascular plants occurring in the Queen Elizabeth Islands

	Vegetation Zones			
	4	3	2	1
I. Imperfectly to moderately drained soils				
A. Woody species				
Cassiope tetragona (L.) Don	p	r	—	—
Dryas integrifolia M. Vahl	d	d	p	—
Salix arctica Pall.	d	d	p	—
Salix polaris Wahlenb.	p	—	—	—
Salix reticulata L.	r	—	—	—
Vaccinium uliginosum L.	r	—	—	—
Rhododendron lapponicum (L.) Wahlenb.	r	—	—	—
B. Vascular cryptogams and ferns				
Lycopodium selago L.	p	r	—	—
Cystopteris fragilis (L.) Bernh.	r	—	—	—
Dryopteris fragrans (L.) Schott.	p	—	—	—
Equisetum arvense L.	p	r	—	—
Equisetum variegatum Schleich.	p	r	—	—
Woodsia alpina (Bolton) S.F. Gray	r	—	—	—
Woodsia glabella (L.) R. Br.	r	—	—	—
C. Principal herbs				
Alopecurus alpinus J.E. Smith	p	p	p	p
Arctagrostis latifolia (R.Br.) Griseb.	p	p	r	—
Festuca baffinensis Polunin	p	p	p	p
Festuca brachyphylla Schultes	p	p	p	p
Festuca richardsonii (Hook)	p	—	—	—
Hierochloe alpina (Sw.) R. & S.	p	r	—	—
Kobresia sp.	p	—	—	—
Poa abbreviata R.Br.	p	p	p	p
Poa alpigena (Fr.) Lindm.	p	p	r	—
Poa arctica R. Br.	p	p	p	p
Carex nardina Fr.	p	r	—	—
Carex rupestris All.	p	r	—	—
Luzula confusa Lindebl.	p	p	d	d
Luzula nivalis (Laest.) Beurl.	p	p	p	p
Polygonum viviparum L.	p	p	r	—
Papaver radicatum Rottb.	p	p	p	p
Cerastium alpinum L.	p	p	p	p
Silene acaulis L.	p	—	—	—
Stellaria longipes Goldie	p	p	p	p
Parrya arctica R. Br.	p	p	—	—
Lesquerella arctica (Wormskj.) S.Wats.	p	p	—	—
Draba bellii Holm	p	p	p	p
Draba alpina L.	p	p	p	p
Braya purpurescens (R.Br.) Bunge	p	p	p	p
Potentilla hyparctica Malte	p	p	p	p
Geum rossii (R.Br.) Ser.	p	—	—	—
Astragalus alpinus (L.)	p	—	—	—
Oxytropis arctica R.Br.	p	—	—	—
Pedicularis lanata Cham. & Schlecht.	p	p	r	—
Pedicularis arctica R. Br.	p	p	—	—
Pedicularis capitata Adams	p	r	—	—
II. Colonizers of disturbed and recently deposited materials				
Equisetum variegatum Scheich.	p	r	r	—
Equisetum arvense L.	p	r	—	—
Alopecurus alpinus J.E. Smith	p	p	p	p
Agropyron violaceum (Hornem.) Lange	p	r	—	—
Festuca sp.	p	p	p	p
Poa sp.	p	p	p	p
Puccinellia sp.	p	p	p	p
Trisetum spicatum (L.) Richt.	p	p	—	—
Luzula confusa Lindbl.	p	p	p	p
Oxyria digyna (L.) Hill	p	p	p	p
Papaver radicatum Rottb.	p	p	p	p
Cerastium alpinum (L.)	p	p	p	p
Stellaria longipes Goldie	p	p	p	p
Melandrium affine J. Vahl	p	r	—	—
Erysimum pallasii (Pursh) Fern.	p	r	—	—
Ranunculus pedatifidus Sm.	p	r	—	—
Saxifraga oppositifolia L.	p	p	p	p
Saxifraga cernua L.	p	p	p	p
Saxifraga tricuspidata Rottb.	p	—	—	—
Saxifraga caespitosa L.	p	p	p	p
Potentilla sp.	p	p	p	p
Epilobium latifolium L.	p	—	—	—
Armeria maritima (Mill.) Willd.	p	r	—	—
Arnica alpina (L.) Olin	p	—	—	—
Antennaria compacta Malte	p	r	—	—
Crepis nana Richards.	p	—	—	—
Erigeron compositus Pursh	p	—	—	—
Erigeron eriocephalus J. Vahl	p	—	—	—
Taraxacum sp.	p	p	r	—
III. Wetland species				
A. Sedges, rushes and grasses				
Carex aquatilis Wahlenb. var. *stans* (Drej.) Boott	d	d	r	—
Carex membranacea Hook.	p	r	—	—
Carex misandra R. Br.	p	r	—	—
Eriophorum callitrix Cham.	p	—	—	—
Eriophorum triste (Th.Fr.) Hadac & Löve	p-d	p-d	r	—
Eriophorum scheuchzeri Hoppe	p	p	r	—
Eriophorum vaginatum L.	r	—	—	—
Alopecurus alpinus J.E. Smith	p	p	d	d
Dupontia fisheri R. Br.	p	p	p	p
Hierochloe pauciflora R. Br.	r	—	—	—
Juncus biglumis L.	p	p	p	p
Luzula nivalis (Laest.) Beurl.	p	p	p	p
B. Secondary herbs on slightly better drained soils				
Cardamine bellidifolia L.	p	p	r	r
Cardamine pratensis L.	p	—	—	—
Cochlearia officinalis L.	p	p	p	p
Eutrema edwardsii R. Br.	p	p	—	—
Saxifraga foliolosa R. Br.	p	p	p	r
Saxifraga hirculis L.	p	p	r	—
Saxifraga nivalis L.	p	p	r	r
Saxifraga rivularis L.	p	p	r	r
Pedicularis sudetica Willd.	p	p	—	—
Petasites frigidus (Banks) A. Gray	p	r	—	—
C. Emergent and submergent species				
Arctophila fulva (Trin.) Rupr.	p	r	—	—
Pleuropogon sabinei R. Br.	p	p	r	—
Ranunculus aquatilis L. var. *subrigidus* (W.B. Drew) Breitung	p	r	—	—
Ranunculus hyperboreus Rottb.	p	p	r	—
Ranunculus gmelini DC	p	p	—	—
Caltha palustris L.	p	—	—	—
Hippuris vulgaris L.	p	—	—	—
VI. Halophytic species				
Puccinellia phryganodes (Trin.) Scribn. & Merr.	p	p	r	—
Carex maritima Gunn.	r	—	—	—
Carex ursina Dew.	r	—	—	—
Stellaria humifusa Rottb.	p	p	r	—
Cochlearia officinalis L.	p	p	p	r
Senecio congestus (R. Br.) DC	r	—	—	—

d = dominant; p = present; r = rare; — = absent.

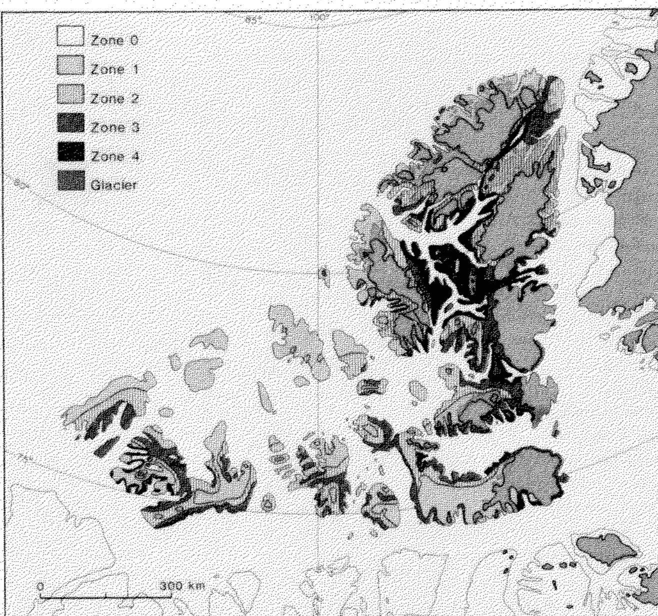

FIG. 5. Vegetation zones of the Queen Elizabeth Island based on the growth forms of the dominant vascular plant species. The zones are summaries of patterns seen on 1:250 000 scale vegetation maps (Edlund, 1982a,b, 1983c,d, 1987b). For greater detail see enlarged figure on page 23.

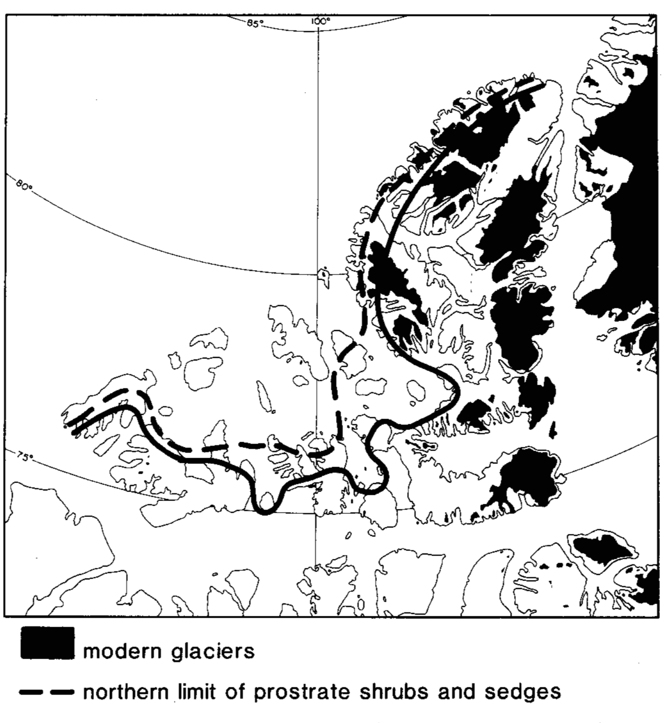

FIG. 6. Regional vegetation potential map showing the best possible vegetation expected, under the best possible soil conditions. This map also assumes topography of near seal level elevation.

equivalent of tree line. Since worldwide ecosystem limits have been closely tied to regional climates, it is essential now to examine the climate of the area within which these newly defined limits occur.

SUMMER CLIMATE PATTERNS IN THE QUEEN ELIZABETH ISLANDS

Introduction

Climate operates on a continuum of time and space scales from micro through to global (Barry, 1970). When studying climate-biosphere interactions, it is important that both be considered on the same time and space scale (Alt and Maxwell, in press). For this reason, with the above regional vegetation patterns and vegetation limits, it is necessary to examine long-term mean values of regional, synoptic or macro-scale climate patterns (Alt and Maxwell, in press). Such examinations should focus on general air mass properties rather than local or meso-scale surface effects. This is not to say that synoptic-scale climate parameters directly influence the physiology of a plant; they rather set the scene within which meso- and micro-scale climate and vegetation interactions take place.

The synoptic-scale climate of the Queen Elizabeth Islands is controlled by a complex interaction of the solar radiation regime, the general atmospheric circulation, and the large-scale topography (Maxwell, 1980, 1982; Alt and Maxwell, in press). The mean (i.e., 30-year normal) regional patterns of climate parameters (such as cloud, temperature, and precipitation) reflect these controls and thus provide a link between general air mass properties and recorded climate information. In the Queen Elizabeth Islands evaluation of these patterns is complicated by two factors: 1) The intricate mosaic of surface conditions within the islands and adjacent waters includes snow-covered mountains, ice caps, valley glaciers, snow-free rocks, bare ground, well-vegetated and poorly vegetated terrain, sea ice, and open water (Fig. 2). Several of these features often occur within a few square kilometres. 2) Climate records began in the late 1940s, and today only four permanent climatological stations cover this vast region (Fig. 2). All are found at near coastal locations; the interiors of the islands are essentially unmonitored.

Methods

It is impossible as yet to present definitive maps showing the regional-scale climate parameters for the Queen Elizabeth Islands. However, vegetation mapping has reached a stage where the link to climate must be examined (Edlund, 1983a, 1986a, 1987a). This is particularly critical in the context of assessing the effects of climatic change, climatic impact, and paleoclimatic interpretations. For this reason the following steps have been taken to maximize the usefulness of the available information so that it might be presented here for initial comparison to vegetation maps, boundaries, and zones.

The sparse weather station data network was augmented by incorporating information from seasonal scientific and oil industry camps (Fig. 2). Only stations with whole months of daily mean records were used. Monthly mean values of short-term stations were adjusted for each year to represent the 1951-80 30-year normals (Atmospheric Environment Service, 1982a), based on the deviation from the 30-year normal at the closest permanent weather station(s). The result was a 30-year normal equivalent value for each field station. This method must be considered a first approximation.

As seen in Figure 2, with the addition of field stations the interior of the Queen Elizabeth Islands is still virtually unrepresented, as even in the Eureka Sound intermontane area most of the stations are on fiords or lakes. To provide a consistent picture of regional climate patterns, contours of the various surface climate parameters were drawn using sea level coastal station values. For each regional sea level coastal contour, a range of values would be found on a meso- or microscale. In the case of screen-level temperature, for instance, the lowest values would be found over the ice-bound channels and the highest at sheltered interior sites. Inland contours have been drawn only when they represent regional-scale features (i.e., 100 km or greater in size). Contours have not been drawn in mountainous areas (over 600 m) or over ice caps (Fig. 2). In drawing details of these sea level contours, consideration was given to the common sea ice patterns and boundaries.

To date, in northern latitudes the best correlations between the type of plant growth and mean regional climate parameters has been obtained using indicators of summer warmth, such as mean July temperature, melting degree days, length of summer season, and incoming solar radiation (Rannie, 1986; Young, 1971; Hustich, 1983; Kauppi and Posch, 1985; Edlund, 1983a, 1986a). Moisture availability has been identified as important only on a meso- or micro-scale. Vegetation is active during the whole summer season, but this season varies with location both in terms of length and time of maximum intensity. Emphasis has been placed on July mean values in the following discussion, for they represent the warmest month at most sites in the Queen Elizabeth Islands. This maximizes the availability of data and allows comparison with other regional studies. June maps have been included where possible, as this is a critical period for breaking of dormancy for many plant species.

Prevailing Atmospheric Circulation

Solar radiation records from the Queen Elizabeth Islands are not adequate to produce realistic regional distribution patterns (Holmgren, 1971; Dahlgren, 1974; Maxwell, 1980; Ohmura, 1981; Alt and Maxwell, in press). Thus it is hoped that the interaction of atmospheric circulation and topography will provide a satisfactory initial understanding of the reasons for the observed patterns of mean cloud, temperature, and precipitation.

In summer the mean flow at all levels of the troposphere is from the central Arctic Ocean into the Queen Elizabeth Islands (Bryson and Hare, 1974; Maxwell, 1980, 1982; Alt, 1987; Alt and Maxwell, in press). This northwesterly flow is illustrated here by July surface streamlines (Fig. 7). In summer the central Arctic Ocean is the coldest region of the northern hemisphere, with the mean July temperature ranging from −1 to 2.5°C (Orvig, 1970). The surface of the moving polar pack ice is extensively puddled, and this moisture source maintains a nearly continuous layer of low stratus and stratocumulus clouds. Studies of air mass source and frequency for North America by both Bryson (1966; Fig. 8) and Barry (1967) show that in July air masses formed over the central Arctic Ocean occupy the Queen Elizabeth Islands more than 90% of the time (Alt and Maxwell, in press).

It should be noted that the northeast corner of Ellesmere Island and the slopes and lowlands facing northern Baffin

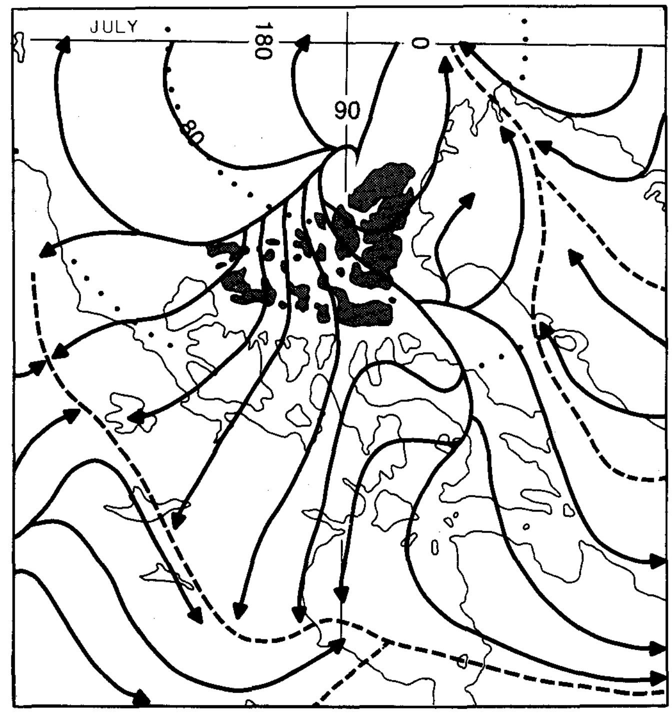

FIG. 7. Surface streamline patterns for July (after Bryson and Hare, 1974). This represents the trajectory a parcel of air would follow.

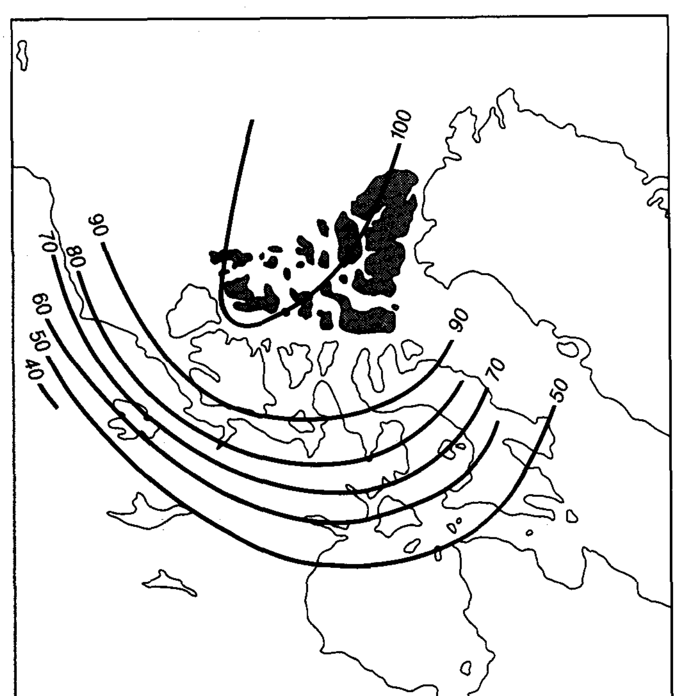

FIG. 8. Frequency of occurrence of air masses of "Arctic origin" (after Bryson, 1966).

Bay cannot be included in these generalities (Maxwell, 1981; Alt and Maxwell, in press) and will not be treated in the discussion that follows.

Cloud Cover

The mean June and July cloud cover maps (Figs. 9a,b) show an S-shaped pattern. Prevailing northwesterly flow drives the extensive stratus and stratocumulus of the central Arctic Ocean into the Sverdrup Lowlands. Over the Eureka Sound intermontane region mean cloud amounts are 20% lower than over the coastal regions bordering the polar pack ice.

The mountains that ring this broad interior region tend to deflect or dissipate the low-level central Arctic Ocean cloud and protect the area in all directions from all but the most persistent travelling cyclonic disturbances (Maxwell, 1982; Alt and Maxwell, in press). In July, when the land areas are snow free, the size and elevation of the southwestern islands also result in dissipation or deflection of the low cloud, reducing regional cloud cover by 5-10% from that of the Sverdrup Lowlands.

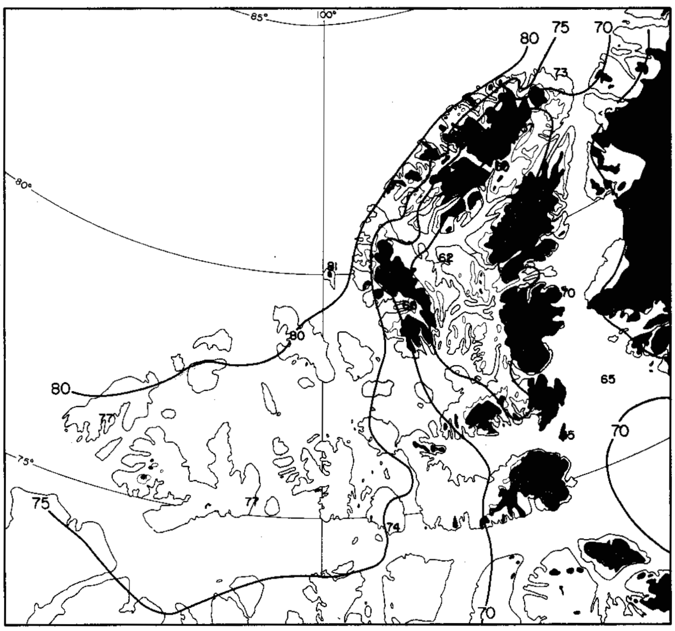

FIG. 9. Mean cloud cover in percent (based on the period 1959-79). Where available field station data were used (corrected as discussed in Figure 11). 9A. June.

Temperature

Lower Troposphere Temperatures: The mean July 90 kPa (ca. 1000 m a.s.l.) temperatures have been plotted to examine the temperatures in the lower atmosphere (Fig. 10). Topography was not taken into account when drawing the contours. These were spaced and shaped as demanded by the values of the five data points alone. The intrusion of cold central Arctic Ocean air over the Sverdrup Lowland and the sheltering effect of the mountain barriers in the east form an S-shaped pattern similar to the cloud patterns. This general S-shaped pattern is thus a macro- or synoptic-scale phenomenon, reaching at least 1000 m into the atmosphere and reflecting the effect of regional-scale topography on the lower troposphere.

Screen-Level Temperatures: Screen-level temperatures provide the link between near-surface micro-climate and air mass characteristics. Mean July screen-level temperatures are the most universally analyzed climatic parameter available and have shown good relationships to regional vegetation patterns in previous studies (Edlund, 1983a, 1986a; Rannie, 1986).

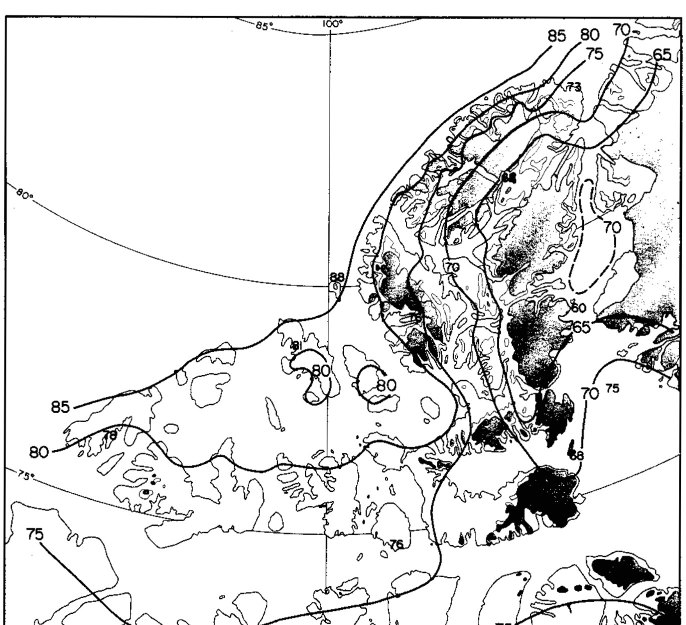

FIG. 9B. July.

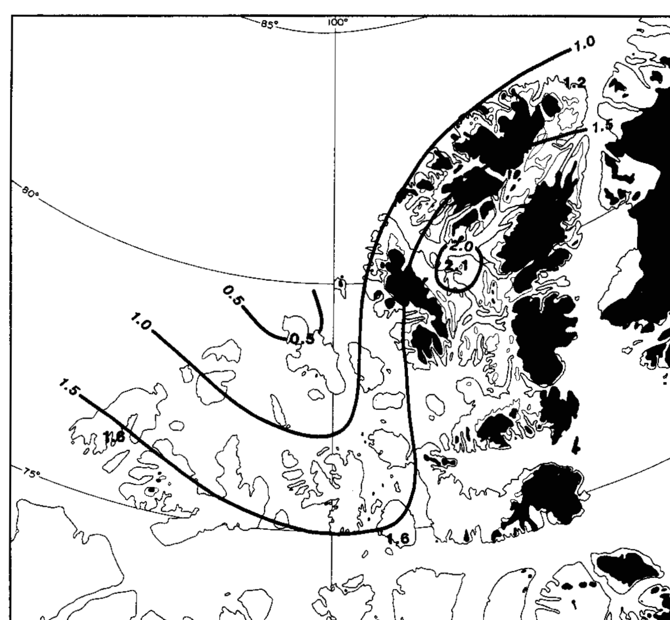

FIG. 10. Mean July temperatures at 90 kPa (ca. 1000 m) for 1951-80 (AES Canadian Climate Centre Data Archive).

A well-defined S-shaped pattern occurs on both the mean June and July maps (Figs. 11a,b). Note that in June, the mean 0°C isotherm separates the warm interior intermontane area from the islands exposed to the air masses from the central Arctic Ocean. In July this dividing line falls between 3 and 4°C, and the sheltered interior is delineated by the 5°C isotherm, the threshold for calculating "effective temperature sum" (Tuhkanen, 1984).

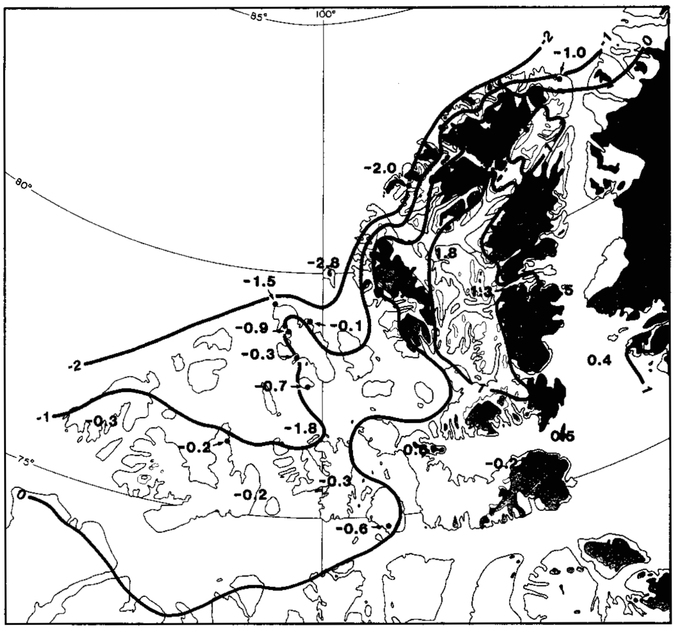

FIG. 11. Mean monthly summer temperatures over the Queen Elizabeth Islands (1951-80 normals). Both permanent weather stations and non-standard weather data were used. A correction factor was applied to the short-term records to produce values for the 1951-80 normal period by comparison with the appropriate permanent weather station records.
11A. June.

FIG. 11B. July.

Initiation and Duration of the Melt Period: The date on which mean daily temperatures rise above freezing (Fig. 12) is earliest in the intermontane region and latest on the low-lying islands. Although this date does not directly reflect the date a site becomes snow free, it is the only available indicator of the beginning of the period of biological activity.

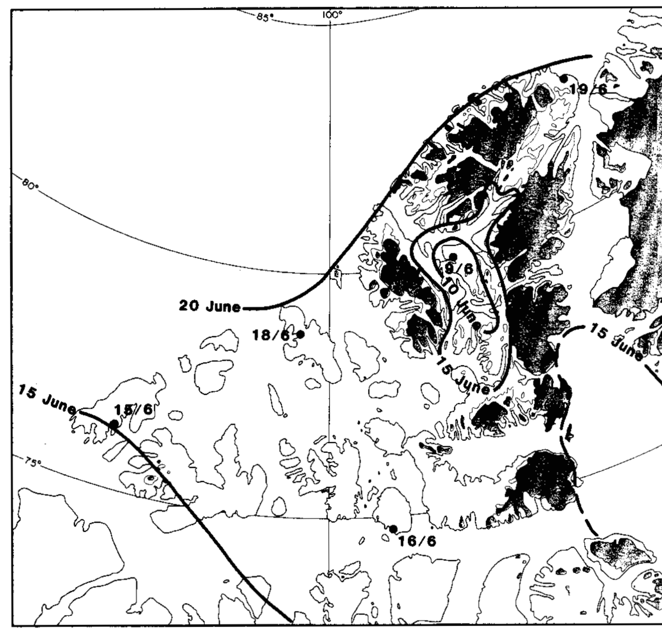

FIG. 12. Mean date of initiation of melt in the Queen Elizabeth Islands (1951-80 normals [AES Canadian Climate Centre Data Archive]).

In the Eureka Sound intermontane area the melt period (Fig. 13) averages 15-20 days longer than in coastal regions adjacent to the polar pack ice. More than half of this extra 20 days is a result of an earlier beginning to the melt season. These 10 days are particularly significant, as solar radiation is at a maximum at this time of year and thus the potential for increased summer warmth is greatest. The maps showing both initiation and duration of melt show the same general S-shaped pattern as the other indicators of summer warmth.

Melting Degree Days: Melting degree day totals are another indicator of the duration and intensity of summer warmth. Melting degree day normals from the permanent stations and adjusted field station values have been contoured (Fig. 14). As would be expected, this parameter also shows the general S-shaped pattern.

Precipitation

Total Precipitation: Precipitation measurements in the Arctic are subject to serious inaccuracies. Winter snow accumulation values from the permanent weather stations appear to be underestimated by 40 to 400% (Koerner, 1979; Maxwell, 1980; Woo *et al.*, 1983).

Mean total annual precipitation, mean total summer precipitation, and mean snow depth on 31 January have been plotted (Figs. 15a,b). Areas over 600 m or covered by ice caps

FIG. 13. Mean duration of melt period in the Queen Elizabeth Islands (1951-80 normals [AES Canadian Climate Centre Data Archive]).

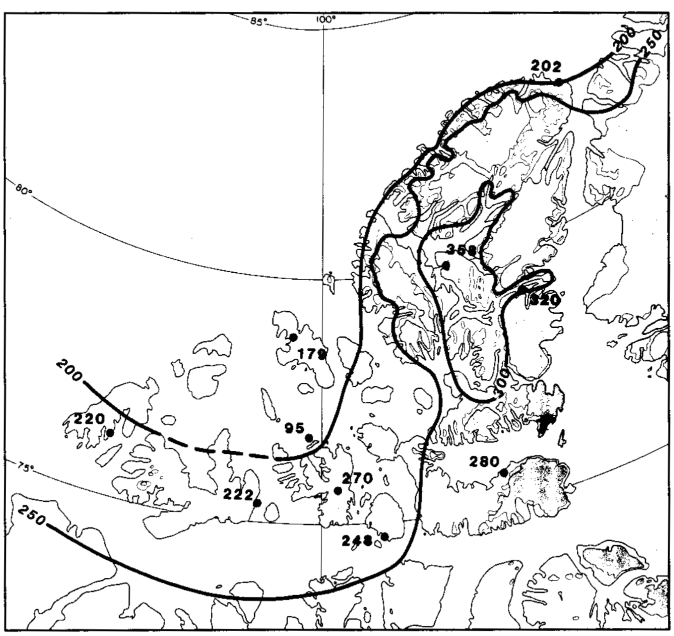

FIG. 14. Mean total seasonal melting degree days from permanent weather stations: 1951-80 normals (Atmospheric Environment Service, 1982b, and non-standard weather stations, corrected as discussed in Figure 11).

have been ignored to be consistent with the regional (near sea level) vegetation and temperature analyses.

Total annual and summer precipitation and winter snow depth values all show similar distributions. The highest precipitation occurs in the area under the direct influence of North Water and the Baffin Bay cyclone. A secondary maximum is found to windward of the mountain barriers on northern Ellesmere and Axel Heiberg islands. Precipitation minimums occur in the Eureka Sound intermontane region due to the rain-shadow effect and in the far western islands due to the proximity of the persistent surface anticyclone.

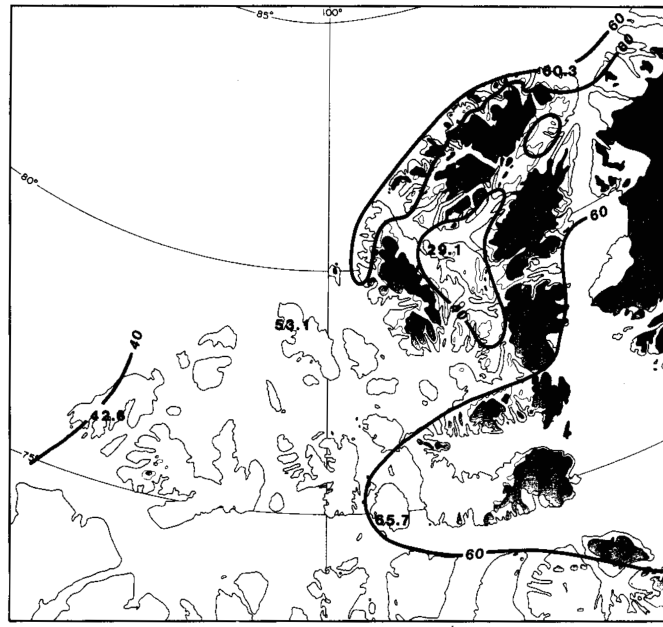

FIG. 15A. Mean total summer (June, July, and August) precipitation (mm) for the Queen Elizabeth Islands (Atmospheric Environment Service, 1982a).

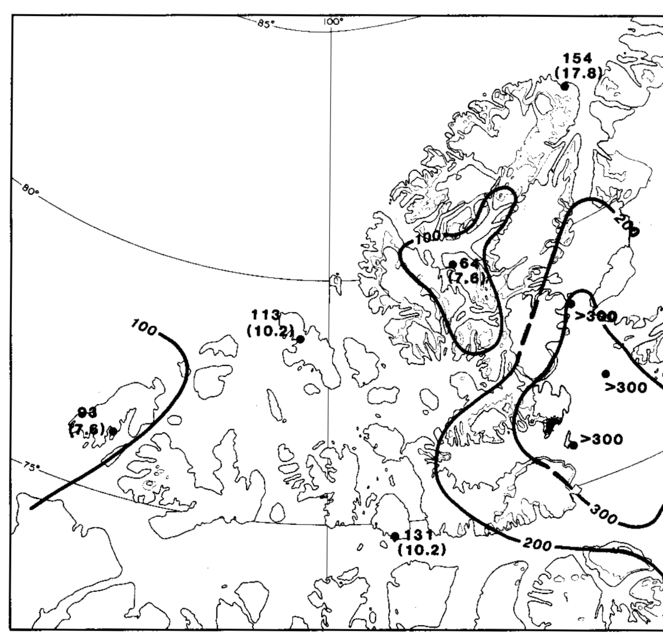

FIG. 15B. Mean annual total precipitation (contours, mm) and snow depth at the end of January (in brackets, cm) (Atmospheric Environment Service, 1982a).

Precipitation amounts thus do not produce the same characteristic S-shaped pattern, as they are controlled by different mechanisms than summer temperature regimes. At a regional scale the major control on precipitation is the frequency and intensity of cyclonic activity, while the interaction of topography and mean atmospheric flow is a secondary effect (Müller *et al.*, 1976; Maxwell, 1980; Bradley and Eischeid, 1985; Alt and Maxwell, in press).

Snow on the Ground: The presence of snow on the ground is a very important parameter, as it not only affects plants directly but also alters the surface energy balance. The number of days between the first snowfall of 2 cm and the last snow depth record of 2 cm or more shows a strong S-shaped pattern (Fig. 16); Mould Bay, Isachson and Resolute all are snow covered for 10-15 days more than Eureka. This is particularly significant in June, when incoming solar radiation energy is at a maximum. The number of years with measured snow on the ground at the end of June (Table 3) further illustrates the extreme contrast between the Eureka intermontane area and the rest of the Queen Elizabeth Islands. Only at Eureka is the ground usually snow free by the end of June. This initial analysis suggests that the regional distribution of the disappearance of snow in the spring is more dependent on spring melt intensity than winter snow accumulation.

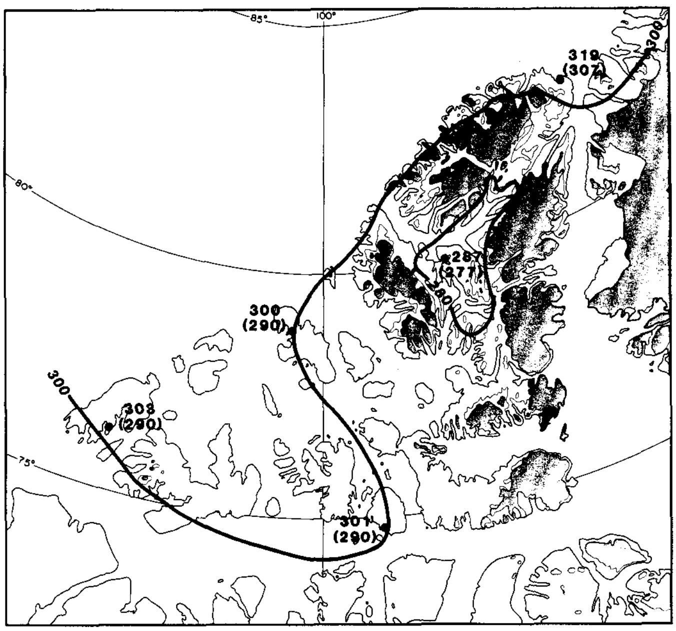

FIG. 16. Duration of snow cover: a) from first day of 2 cm snow cover to last day of 2 cm snow cover (analyzed); b) from first day of persistent (lasting 7 days) snow cover of 2 cm to last day of persistent snow cover, from 1951-80 normals (AES Canadian Climate Centre Data Archive).

TABLE 3. Number of years with snow present on the ground at the end of June

Arctic Weather Station	No. of Years (out of 18)
Alert, Ellesmere Island	13/18
Eureka, Ellesmere Island	3/18
Isachsen, Ellef Ringnes Island	10/18
Mould Bay, Prince Patrick Island	9/18
Resolute, Cornwallis Island	13/18
Sachs Harbour, Banks Island	4/18

DISCUSSION

There is a striking resemblance between regional vegetation patterns and the mean cloud and temperature regimes. The lowest summer temperatures occur in the regions under the greatest influence of central Arctic Ocean climate. Persistent low cloud cover, fog, low temperatures, and shortest snow-free season make this the harshest regional summer climate in North America. This corresponds to the area of least diversity, lowest percentage cover of vascular plant species, and dominated by herbaceous species.

The highest summer temperatures occur in the protected Eureka Sound intermontane region, where the lowest cloud amounts and least precipitation occur. This area also has the longest snow-free period and the longest period with temperatures above 0°C.

Between these two extremes are regions with intermediate values for both climate severity and vegetation diversity. Woody plants and sedges dominate the warmer sectors; with decreasing temperatures, dominance of both is lost, and both density and diversity decrease. Woody species are replaced by herbaceous species and sedges by grasses in the coolest sectors.

The congruence is most evident when comparing the characteristic S-shaped patterns of vegetation limits (Fig. 6) with mean July temperatures (Fig. 11b). It is important to remember that both these patterns were derived on a regional scale neglecting the effects of elevation, local topography, and meso-scale climate. The regional vegetation patterns reflect the best possible vegetation that can be expected if materials were capable of supporting plant growth and adequate moisture was available. The temperature patterns, on the other hand, reflect the air mass temperature as deduced from screen-level temperatures at coastal stations.

The coincidence of these patterns (Figs. 6, 11b) allows us to tie major phytogeographic limits roughly to mean July isotherms. The boundary between zones 3 and 2 defines the northern limit of plant communities dominated by woody species; and the boundary between zones 2 and 1 marks the northern limit of woody plants. Woody plant species do not occur in areas with regional mean daily July temperatures below 3°C. Dominance of woody plants occurs in areas where local mean daily July temperatures are greater than 4°C and woody species, including heath species, flourish well in areas with mean daily July temperatures greater than 5°C.

There is a strong precedent for this regional-synoptic-scale approach. In studies of climate and the boreal forest ecosystem to the south, Bryson (1966) has shown that the southern boundary of the boreal forest coincides roughly with the mean winter position of the arctic front and the northern forest limit lies close to the mean summer position of the arctic front. Larsen (1971, 1974) emphasizes the origins and frequencies of air masses in summer and their effect on the distribution of plant species in the boreal forest. Singh and Powell (1986) also show the strong influence of climate on the boreal forest of western Canada.

The positions of forest limits and tree line have long been tied to isotherms. Tree line roughly coincides with the 10°C mean daily July temperature (Nordenskjöld and Mecking, 1928; Köppen, 1923). Hare (1970) also evokes this limit for tree line in North America and suggests that the northern boreal forest limit roughly coincides with the 13°C mean July temperature. Timberline, the alpine limit of tree growth, also appears to correspond to the 10°C mean July temperature (Tranquilini, 1979).

Bioclimatic Zones

The high degree of congruence between regional climate patterns and vegetation zones allows broad climatic descriptions to be applied to the regional vegetation zones, converting them to bioclimatic zones. Distribution maps of these bioclimatic zones will enable initial evaluation of the climate in areas where climatic observations are not available.

Zone 0 — Vegetation-Free Zone: Zone 0, characterized by a lack of both vascular plant and cryptogamic vegetation, occurs on the highlands and plateaus of Melville Island (Edlund, 1985) and Bathurst Island (Edlund, 1982b). Although not yet aerially mapped, this zone probably occurs on some ice-free summits of Axel Heiberg and Ellesmere islands (Beschel, 1961, 1970). Though small in comparison to other vegetation zones, zone 0 covers major areas on the plateaus and highlands of Melville Island, above 350-400 m a.s.l. The larger areas in this zone range from 400 to 740 km^2 and together total more than 2500 km^2 (Edlund, 1985).

The full regional extent of zone 0 is not known, for it can only be detected in areas where materials are capable of supporting either cryptogamic or vascular plants. Areas of high elevation, but with materials inimical to plant growth, have been omitted from this zone.

On Melville Island this zone is roughly concentric, with small ice caps found on the Blue Hills and other plateaus of western Melville Island, but it also occurs on major plateaus lacking ice caps, such as the Raglan Range north of McCormick Inlet and the plateaus east of Weatherall Bay.

Zone 0 is commonly blanketed by low stratus and stratocumulus clouds for much of summer. Snow falls at any time during the summer and may remain on the ground for days or weeks. Zone 0 is the latest zone to thaw in the spring, the first to freeze up in late summer, and roughly corresponds to equilibrium line calculations for glaciation levels or freezing levels (Bradley, 1975; Bradley and Eischeid, 1985). Summer temperatures in this zone are so low (mean July temperatures near 0°C) that lee slope snowbanks commonly persist throughout the summer. Melting degree days probably total less than 50. Snow-free days with mean temperatures above freezing total considerably less than 3-4 weeks on Melville Island, possibly a week or less (Edlund, field notes 1984, 1985). This climate most closely approximates conditions found on the central Arctic Ocean described by Vowinckel and Orvig (1970).

This zone may also occur in a narrow coastal band along the rim of the Queen Elizabeth Islands directly adjacent to the polar pack ice. This has yet to be documented.

Zone 1 — Herbaceous Zone: Zone 1 is the zone in which vascular plants are sparsest, least diverse, and entirely herbaceous. This is the most common type of vegetation of the low-lying northwestern and north-central Queen Elizabeth Islands. It is profoundly influenced by air moving directly off the central Arctic Ocean. The ice-bound inter-island channels maintain the low temperature and high moisture characteristics of this air mass. In June, most of the land is snow covered, and consequently little modification of the air mass occurs even over land. By July the larger islands can locally modify the air mass, due to radiative heating from the snow-free ground surfaces. But the continuous inter-island ice is extensive enough that the general characteristics of the air mass are maintained.

The mean June temperature is below freezing (0 to −2°C), with less than 1°C separating sea ice and land sites. The mean July temperatures on land are less than 3°C. Snow cover persists in this zone into early July. Small perennial snow beds are common on lee-side slopes (commonly south to southeast facing due to the accumulation of snow on the lee-side slopes) and in ravines. Freeze-up begins as early as mid-August. The melt season is limited to about 9 weeks, while the snow-free period, with temperatures above 0°C, is perhaps only 6-7 weeks. Melting degree days totals range between 50 and 150.

This zone is also found on the uplands of the southern Queen Elizabeth Islands at elevations above 150-200 m (Edlund, 1982b, 1983c) and in some places at elevations above 200-500 m in the more mountainous regions.

Pockets of slightly richer vascular plant assemblages occur in a few sheltered valleys and on sunny, snow-free, south-facing slopes (Edlund, 1983a; Savile, 1971). However, these richer areas are micro- and meso-scale features and thus do not alter the regional picture.

Zone 2 — Herb-Shrub Transition Zone: In zone 2 the vascular plant component is dominated by herbaceous species as in zone 1; however, species diversity has increased and in some places is double that present in zone 1. Both dwarf shrubs and sedges regularly appear locally but never dominate. This zone can be viewed as transitional between zones 1 and 3.

Snow lingers into late June or early July in this zone and local perennial snow beds persist throughout the summer in many places, but they are generally not as common or as large as those in zone 1. Although mean June temperatures are still below freezing, mean July temperatures may reach 3.1-3.9°C. During July, the more extensive snow-free land areas cause some modification of the central Arctic Ocean air mass. The melt season varies from 8 to 10 weeks, while the snow-free period is generally only 7-9 weeks. Melting degree days totals range between 150 and 250.

Near sea level this zone appears to coincide with areas where the sea ice of the inter-island channels breaks up in mid-summer, leaving extensive areas of open water adjacent to the islands. Cloud amounts remain high because of the availability of moisture from such open water, and fog is therefore frequent.

This zone is common only near sea level on the leeward sides of the northwestern islands, at intermediate elevations (ca. 100-150 m) in the southern uplands, and at elevations ranging upward of 800 m on the leeward side of the mountains in the northeast.

Zone 3 — Prostrate Shrub Zone: The vascular plant component of zone 3 is dominated by prostrate and matted shrubs on mesic sites and in wet areas by sedges. This zone occurs near sea level in the southern Queen Elizabeth Islands, as well as on the northern coast of Devon and some of the larger central islands, generally in the lee of sizable land masses. Snow generally disappears by mid-June and perennial snow beds are present but not abundant. The temperature and cloud cover regimes over these regions are somewhat modified once the ground is snow free. Air flow from more southerly regions may play a limited part in the earlier disappearance of snow cover.

Mean temperatures in June are above freezing; mean temperatures in July are at least 4°C and approach 5°C. The melt season is at least 10 weeks long, and as the snow tends to disappear rapidly, the snow-free period is over 9 weeks. Melting degree days totals range between 250 and 350.

Zone 3 includes southern and southeastern Prince Patrick Island, southern and western Melville Island, southern and central lowlands of Bathurst and Cornwallis, and the coastal regions of Devon Island.

Zone 4 — Enriched Prostrate Shrub Zone: Zone 4 has the greatest density and diversity of vascular plant species in the Queen Elizabeth Islands. Prostrate and matted shrubs and sedges dominate, as in zone 3; however, it is readily separated from zone 3 by the increase in diversity (100-150 taxa), for a number of more southerly species regularly occur in all communities and in pioneering habitats (Table 2).

It is best known in the intermontane area, where it is documented by Eureka the "Garden Spot of the Arctic," Lake Hazen, and Tanquary Fiord. Smaller areas of western and southern Melville rival the intermontane area with nearly equal diversity and abundance of vascular plants and have in common many disjunct species (Edlund, 1986b, 1987b, in press).

Zone 4 is not only sheltered from the direct effects of air masses originating over the polar pack ice by the substantial mountain and plateau barriers, but also experiences cloud minimums and low relative humidity associated with broad-scale subsidence in the lee of the mountains (Alt and Maxwell, in press). The land is generally snow free by early to mid-June. Temperatures in June are well above freezing and in some places reach as high as 4°C. In July mean monthly temperatures exceed 5°C; King (1981) reports mean July temperatures of over 8°C. The melt season may be as long as 12 weeks, while the snow-free period is at least 10-11 weeks. Melting degree days totals are greater than 350.

In contrast to the rest of the Queen Elizabeth Islands, this zone is unlikely to experience mean daily temperatures below freezing once the melt season is established. This allows disjunct distribution for plants with more temperate requirements.

The intermontane area has the lowest precipitation amounts in the Queen Elizabeth Islands, in some areas with less than 40 mm annually (England *et al.*, 1981). This does not represent moisture availability, as it is coincident with the lushest vegetation.

Oases: The concept of oases is a popular one in the Arctic (Svoboda and Freedman, 1981). It implies locally fertile areas in the midst of desert, due to local sources of water. In the Arctic local fertility can be enhanced in several ways. Seepage slopes with abundant water supply throughout the summer can create an oasis. Dark-coloured substrates, sheltered valleys, or snow-free south-facing slopes, locally warmer than the surrounding terrain, may create a thermal oasis. With an adequate supply of water these areas can be richer than adjacent light-coloured materials. Materials that contain an unusually high amount of nitrogen or phosphorus, such as areas adjacent to burrows, dens, or bird cliffs, show greatly enhanced vegetation growth.

Oases are the most intensively studied areas, but these cannot be taken as representative of the region, for the total area covered by most oases is less than 5 km^2, a micro- or meso-scale feature rather than a regional one. They usually represent the best plant productivity of a region under ideal conditions and may be of great local or seasonal importance to fauna. Regional bioclimatic studies provide a background to which the oases or enriched areas can be compared and evaluated.

Floristics and Regional Climate Patterns

The regional presence of the most common shrubs, *Salix arctica* (Fig. 17a) and *Dryas integrifolia* (Fig. 17c), therefore suggests that critical minimum mean July temperatures of at least 3°C have been reached. Woody ericaceous species *Cassiope tetragona*, *Vaccinium uliginosum*, and *Rhododendron lapponicum* (Fig. 17b) show disjunct distributions in the High Arctic. In addition to their clear preferences for neutral to acid soils, *Vaccinium* species are found in the warmest areas of the intermontane region. *Cassiope tetragona* is found abundantly there as well and in warm valleys and lowlands of Melville, Bathurst, and Devon islands, often on south-facing slopes, on dark substrates, or where mean July temperatures are at least 5°C.

Salix polaris (Fig. 17a), found only in zone 4, shows a dual disjunct distribution in the Queen Elizabeth Islands. It occurs in the Fosheim Peninsula, Ellesmere Island (J. Inglis, pers. comm. 1976), and on southwestern Melville Island (Edlund, herbarium accession no. 499653). *Salix herbacea* and *S. reticulata* (Fig. 17a), as well as *Empetrum nigrum* (Fig. 17b), are limited to the warmest areas of the northeastern Queen Elizabeth Islands (Porsild, 1964).

Many herbaceous species and entire families reach their northern limits within the boundaries of the Queen Elizabeth Islands. In the western sector, Leguminosae (Fig. 17d) such as *Oxytropis arctica*, *O. arctobia*, and *Astragalus alpinus* are abundant on neutral to weakly alkaline soils in zone 4 (Edlund, 1986a,b, 1987b). In some places they are as abundant as in the mid-arctic regions of Victoria and Banks islands (Edlund, 1983b; Vincent and Edlund, 1978). Leguminosae occur in no other area of the Queen Elizabeth Islands, although they are widely distributed south of Parry Channel (Porsild and Cody, 1980).

Although all Leguminosae on Melville Island flowered profusely in late June and early July 1984 and 1985, no viable seed or even signs of seed development could be detected in plants collected in mid-August. This indicates that these species are at the edge of physiological tolerance and may have become established at these sites prior to the current climate regime. Sections through nodulated roots of *Astragalus alpinus* and *Oxytropis arctica* from McCormick and Minto inlets suggest that they are several decades old (H. Shulmann, pers. comm. 1986).

Compositae, with the exception of the High Arctic endemic *Taraxacum* species, are also found only in the warmest regions (zones 3 and 4) and locally in thermal oases. Species such as *Crepis nana* (Herbarium accession numbers 496101, 502460 and 502552), *Petasites frigidus*, and *Senecio congestus* (Fig. 17g) occur only on southeastern Prince Patrick Island and warm areas of western Melville Island (Kuc, 1970; Porsild and Cody, 1980; Edlund, 1986a). Other Compositae show the dual disjunct distribution similar to that of *Salix polaris*, occurring only in zone 4 on both Melville Island and in the intermontane area. These include *Antennaria compacta* (Herbarium accession numbers 499551, 496733, 500052, 500056, and 502650), *Arnica alpina* ssp. *angustifolia* (Herbarium accession numbers 495896, 496098, 499956, 499906, 496758, and 502546), *Erigeron compositus*, and *E. eriocephalus* (Fig. 17h) (Porsild and Cody, 1980; Edlund, 1986a).

Several other species also show this dual disjunct distribution. *Geum rossii* (Fig. 17c), an Amphi-beringian species found in Canada in the unglaciated regions of the Yukon and again in the Queen Elizabeth Islands in zone 4, occurs on both Melville Island and the intermontane area (Porsild and Cody, 1980; Edlund, 1986a). In both widely separated areas it is restricted to moderately to imperfectly drained, weakly alkaline soils, usually tills and marine reworked deposits that have a variety of plant nutrients.

Erysimum pallasii, Epilobium latifolium, E. arcticum, Hippuris vulgaris, Androsace septentrionalis (Fig. 17e), and *Py-*

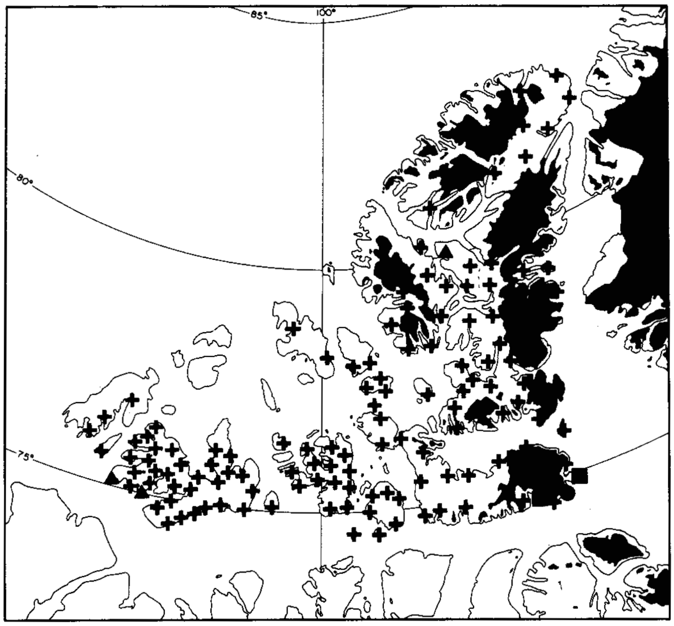

FIG. 17. Distribution of selected vascular plants in the Queen Elizabeth Islands.
17A. Salicacae.

FIG. 17C. Rosaceae.

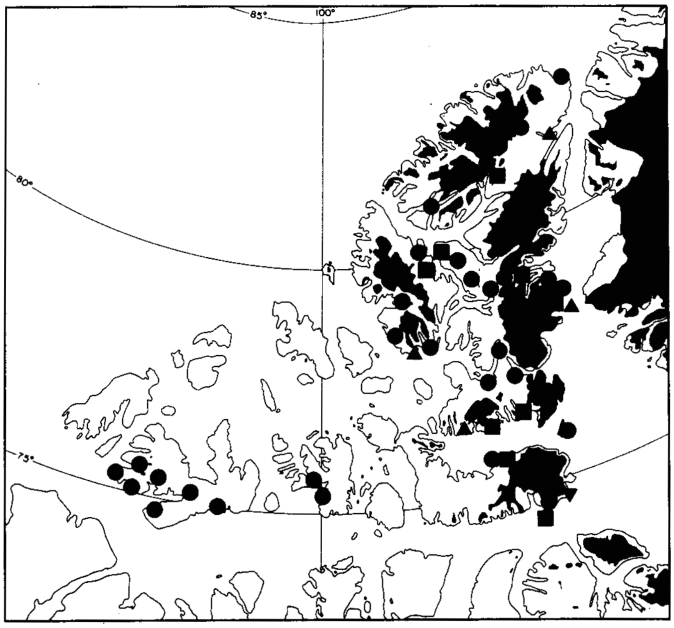

FIG. 17B. Ericaceae and Empetraceae.

FIG. 17D. Leguminosae.

rola grandiflora (Herbarium accession no. 499908; Cody *et al.*, 1976; Porsild and Cody, 1980; Edlund, 1986a) also show the dual disjunct distribution.

Ranunculaceae (Fig. 17f) such as *Ranunculus hyperboreus*, like *R. sabinei* and *R. sulphureus*, are widespread throughout the Arctic Archipelago, although *Ranunculus hyperboreus* is rarely present in zone 1 (Porsild and Cody, 1980). *Ranunculus gmelini* and *Caltha palustris* var. *arctica* (Cody *et al.*, 1976; Porsild and Cody, 1980; Edlund, 1986a) occur in the warmest sector of the southwestern Queen Elizabeth Islands,

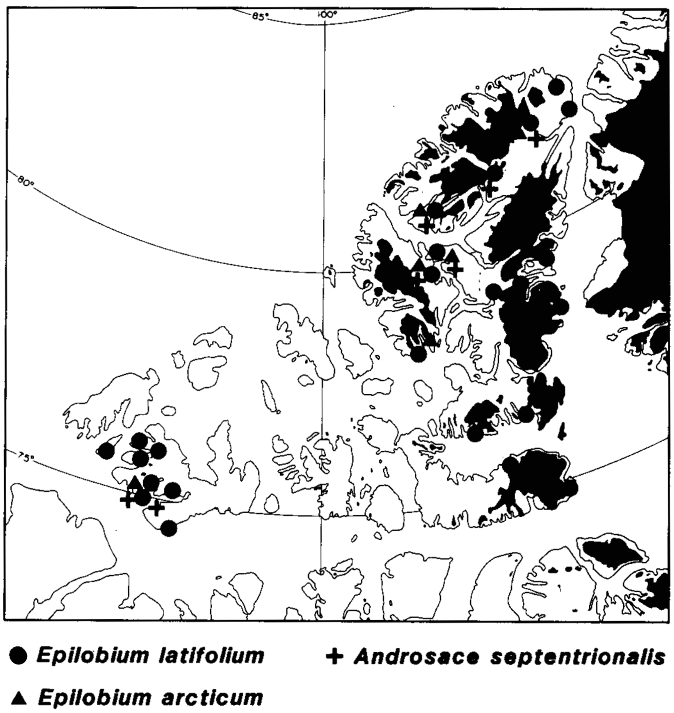

FIG. 17E. Onagraceae and Primulaceae.

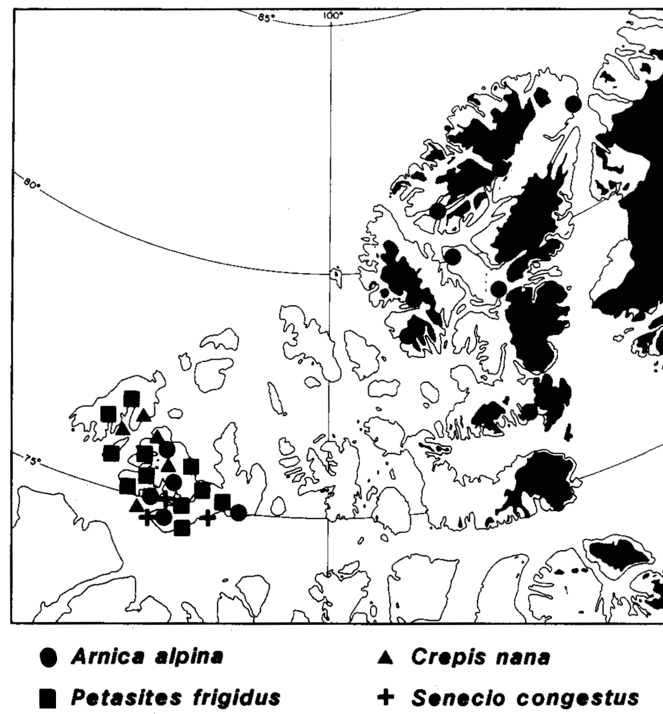

FIG. 17G. Compositae (I).

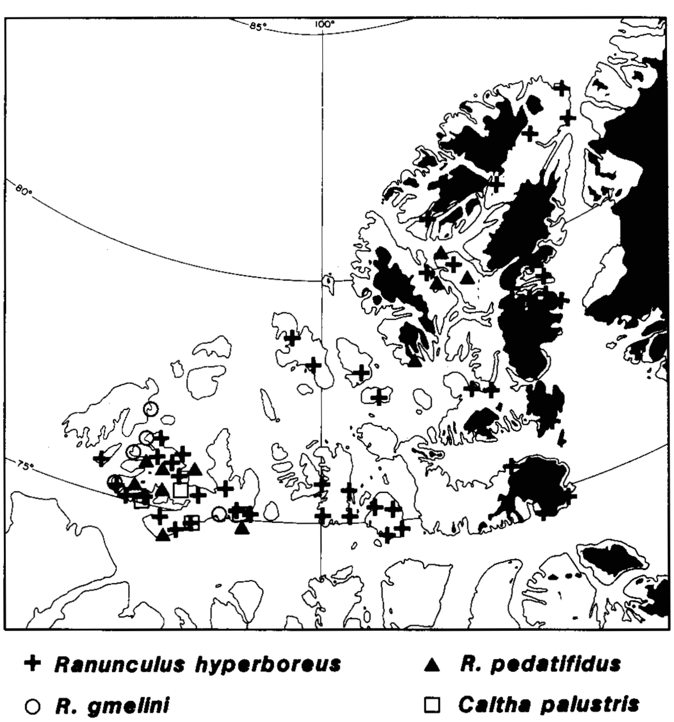

FIG. 17F. Ranunculaceae.

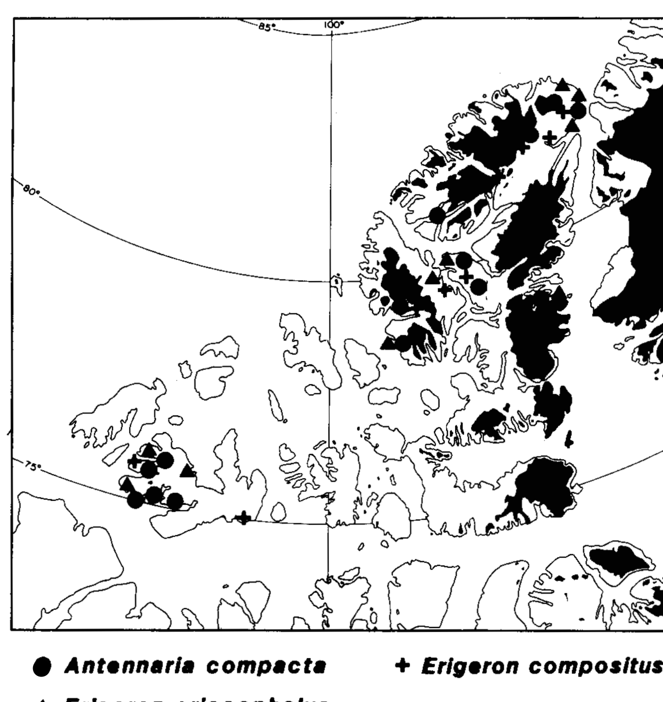

FIG. 17H. Compositae (II).

while *Ranunculus pedatifidus* has the dual disjunct distribution.

The solitary and dual disjunct patterns of many of the species in the Queen Elizabeth Islands suggest that these species have strict materials and/or temperature requirements met only in the warmest zones. Species with somewhat more temperate requirements may show restricted ranges because of problems of migration into other habitable areas. Some species that probably would thrive in the intermontane zone of the northeastern Queen Elizabeth Islands, such as Leguminosae and Compositae, would have to cross uninhabitable inter-island channels, vast expanses of highly alkaline soils, and inhospitable mountainous regions with extensive ice caps and would have to migrate against the prevailing winds. It is remarkable that so many species have successfully made such a migration.

The growth forms of several herbaceous species show marked changes within the Queen Elizabeth Islands. Forbs capable of producing tall flowering stalks (between 20 cm to more than 1 m), such as *Petasites frigidus*, *Senecio congestus*, *Arnica alpina*, and *Epilobium latifolium*, are also found in the warmest sectors of the Queen Elizabeth Islands. Even in zone 4, however, they usually are generally greatly reduced in height. A tall, erect growth form was only seen in a few specimens from sheltered and south-facing slopes. The number of flowers produced also is greatly reduced. In the southern Arctic *Senecio congestus* is a multi-flowered cyme, 80-100 cm high. On Melville Island, *Senecio congestus*, at its northwestern limit, was never observed to have more than one or two flowers and the stem was extremely dwarfed, never taller than 6 cm. *Petasites frigidus*, which reaches 50-80 cm height in the south, rarely tops 10 cm on Melville Island. Its flower numbers are reduced to only four or five. *Epilobium latifolium*, 30-40 cm high in the southern Arctic, is prostrate in zone 4 on Melville Island and rarely has more than a few flowers (Edlund, 1987a). In some places in the intermontane zone it locally shows the more typical erect growth form.

CONCLUSIONS

Summer climate, particularly as reflected by regional mean July temperature distributions, greatly influences the distribution of vegetation in this region, where most vascular plant species are at or near their physiological limits of tolerance. This is seen in the decrease in taxa in the various zones, in the floristic distributions of individual species, in the changes in types of growth forms, and in the dominance of certain growth forms and species.

Several major phytogeographic limits occur in this region, including the northern limits of prostrate and matted shrubs, heath species, and sedges and of the dominance of woody species and of sedges.

The Queen Elizabeth Islands have been divided into five bioclimatic zones, and the summer climate parameters of each zone are described. The more favourable the climate, the greater the significance, diversity, and abundance of woody species, sedges, and other herbs.

The harshest bioclimatic zones (0 and 1) border on the limit of physiological tolerance. No vegetation occurs in zone 0, due to the extremely low summer temperatures and the extremely short melt season – a few days to a few weeks. In zone 1, which is entirely herbaceous, vascular species are few and the most successful species are those capable of flowering early in the snow-free period.

Wood species and sedges appear in zone 2, but it, like zone 1, is dominated by herbaceous species. This may be considered a transition zone between the entirely herbaceous zone and the zones dominated by woody plants.

Woody species and sedges become dominant in zone 3, where mean July temperatures are at least 4°C. Diversity increases in this zone as well. This zone represents the "best" vegetation over much of the central and western Queen Elizabeth Islands.

Zone 4, the warmest zone, has the greatest density and diversity of vascular plants. Here is found the northern limit of many species common farther south, including many that do not flower until late July or early August. Zone 4 regional distribution is discontinuous, mappable only on southern and western Melville Island and in the intermontane region. The intermontane zone that supports the richest vegetation coincides with the area of least regional precipitation, suggesting that precipitation is not a limiting factor to arctic vegetation on a regional scale.

Preliminary work suggests that climate also controls the stature of a few species, which become dwarfed or prostrate with increasing severity of climate. Several vascular plant species show promise as bioclimatic indicators, particularly woody plants, including *Salix* and *Dryas* and sedges, as well as numerous forbs, especially Leguminosae, Onagraceae, and Compositae. The vegetation-climate relationships outlined in this paper may prove useful for mapping mean summer climate in data-sparse regions.

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REFERENCES

ADDISON, P.A., and BLISS, L.C. 1980. Summer climate, microclimate and energy budget of a polar semi-desert on King Christian Island, N.W.T., Canada. Arctic and Alpine Research 12(1):161-170.

ALEKSANDROVA, V.D. 1980. The Arctic and Antarctic: their division into geobotanical areas. (Translated from Russian by D. Löve.) London: Cambridge University Press. 247 p.

ALEXANDROVA, V.D. 1970. The vegetation of the tundra zones in the U.S.S.R. and data about its productivity. In: Fuller, W.A., and Kevan, P.G., eds. Proceedings, Conference on Productivity and Conservation in Northern Circumpolar Lands, International Union for Conservation of Nature, New Series no. 16:93-114.

ALT, B.T. 1979. Investigation of summer synoptic climate controls on the mass balance of Meighen Ice Cap. Atmosphere-Ocean 17(3):181-199.

______. 1987. Developing synoptic analogs for extreme mass balance conditions on Queen Elizabeth Islands ice caps. Journal of Climate and Applied Meteorology 26(12):1605-1623.

______ and MAXWELL, J.B. In press. The Queen Elizabeth Islands: A case study for arctic climate data availability and regional climate analysis. In: Harington, C.R., ed. Symposium on the Canadian Arctic Islands, Canada's missing dimension. Special Publication, National Museum of Natural Sciences.

ARKAY, K.E.E. 1972. Species distribution and biomass characteristics of the terrestrial vascular flora, Resolute, N.W.T. M.Sc. thesis, Department of Geography, McGill University, Montreal, Quebec. 146 p.

ATMOSPHERIC ENVIRONMENT SERVICE. 1982a. Canadian Climate Normals 1951-1980, the North: Y.T. and N.W.T., Temperature and Precipitation. Downsview, Ontario: Environment Canada. 55 p.

______. 1982b. Canadian Climate Normals 1951-1980, Volume 4: Degree Days. Downsview, Ontario: Environment Canada. 280 p.

BABB, T.A., and BLISS, L.C. 1974. Susceptibility to environmental impact in the Queen Elizabeth Islands. Arctic 27(3):234-236.

BARNETT, D.M., EDLUND, S.A., DREDGE, L.A., THOMAS, D.C., and PREVETT, L.S. 1975. Terrain classification and evaluation, eastern Melville Island, N.W.T. Geological Survey of Canada, Open File 252. 2 vols. 1318 p.,

BARRETT, P.E. 1972. Phytogeocoenoses of a coastal lowland ecosystem, Devon Island, N.W.T. Ph.D. thesis, Department of Botany, University of British Columbia, Vancouver, B.C. 293 p.

______ and TEERI, J.A. 1973. Vascular plants of the Truelove Inlet region, Devon Island. Arctic 26(1):58-67.

BARRY, R.G. 1967. Seasonal location of the Arctic front over North America. Geographical Bulletin 9(2):79-95.

______. 1970. A framework for climatological research with particular reference to scale concepts. Institute of British Geographers Transactions 49:61-70.

______ and JACKSON, C.I. 1969. Summer weather conditions at Tanquary Fiord, N.W.T. 1963-1967. Arctic and Alpine Research 1(3):169-180.

BELL, K.L., and BLISS, L.C. 1977a. Overwinter phenology of plants in a polar semidesert. Arctic 30(2):118-121.

______. 1977b. Root growth in a Polar semi-desert environment. Canadian Journal of Botany 56:2470-2490.

BESCHEL, R.E. 1961. Botany and some remarks on the history of vegetation and glacierization. In: Muller, B.S., ed. Axel Heiberg Island, Preliminary Report 1959-1960. Montreal: McGill University. 179-199.

______. 1962. Geobotanical studies on Axel Heiberg Island, 1962. In: Müller, F., ed. Axel Heiberg Island Research Reports, Preliminary Report 1961-62. Montreal: McGill University. 199-215.

______. 1969. Floristicheskie Sootnosheniyz na ostrovakh Neoarktiki. (Floristic relations of the Nearctic Islands.) (Translated by Canada, Secretary of State.) Botanicheski Xhurnal 54(6):872-891.

______. 1970. The diversity of tundra vegetation. In: Fuller, W.A., and Kevan, P.J., eds. Proceedings, Conference on Productivity and Conservation in Northern Circumpolar Lands, Edmonton, Alberta, 1969. International Union for Conservation of Nature, New Series 16:85-92.

BLISS, L.C. 1975. Tundra grasslands, herblands and shrublands and the role of herbivores. Geoscience and Man 10:51-79.

______, ed. 1977. Truelove Lowland, Devon Island, Canada: a High Arctic ecosystem. Edmonton: University of Alberta Press. 714 p.

______ and SVOBODA, J. 1984. Plant communities and plant production in the western Queen Elizabeth Islands. Holarctic Ecology 7:325-344.

______ and BLISS, D.I. 1984. Polar deserts, their plant cover and plant production in the Canadian High Arctic. Holarctic Ecology 7:305-324.

BOSTOCK, H.S. 1967. Physiographic regions of Canada. Geological Survey of Canada Map No. 1254A.

BRADLEY, R.S. 1975. Equilibrium line altitudes, mass balance and July freezing level heights in the Canadian High Arctic. Journal of Glaciology 14:267-274.

______ and EISCHEID, J.K. 1985. Aspects of the precipitation climatology of the Canadian High Arctic. In: Bradley, R.S., ed. Glacial Geologic and Glacio-climatic studies in the Canadian High Arctic. University of Massachusetts, Amherst, Massachusetts, Contribution No. 49: 250-271.

BRASSARD, G.R., and BESCHEL, R.E. 1968. The vascular flora of Tanquary Fiord, northern Ellesmere Island, N.W.T. Canadian Field-Naturalist 82(2):103-113.

BRASSARD, G.R., and LONGTON, R.G. 1970. The flora and vegetation of Van Hauen Pass, northwestern Ellesmere Island. Canadian Field-Naturalist 84:357-364.

BRIDGLAND, J., and GILLETT, J.M. 1984. Vascular plants of the Hayes Sound region, Ellesmere Island, Northwest Territories. Canadian Field-Naturalist 97:279-292.

BRUGGEMANN, P.F., and CALDER, J.A. 1953. Botanical investigations in northeast Ellesmere Island, 1951. Canadian Field-Naturalist 67(4):157-174.

BRYSON, R.A. 1966. Air masses, streamlines and the boreal forest. Geographical Bulletin 8(3):228-269.

______ and HARE, F.K., eds. 1974. Climates of North America. World Survey of Climatology, Vol. 11. Amsterdam: Elsevier. 420 p.

CODY, W.J., PARKER, G.R., and LAMPERT, D.B.M. 1976. Additions to the vascular flora of Melville Island, Franklin District, Northwest Territories. Canadian Field-Naturalist 90:70-72.

DAHLGREN, L. 1974. Solar radiation climate near sea level in the Canadian Arctic Archipelago. Uppsala, Sweden: Meteorologiska Institutionen, Uppsala Universitet Meddelande Nr. 121. 119 p.

DANSEREAU, P. 1957. Biogeography, an Ecological Perspective. New York: The Ronald Press Company. 394 p.

DYKE, A.S., and PREST, V.K. 1987. Late Wisconsinan and Holocene history of the Laurentide Ice Sheet. Géographie physique et Quaternaire XLI(2):237-263.

EDLUND, S.A. 1980. Vegetation of Lougheed Island, District of Franklin. In: Current Research, Part A, Geological Survey of Canada, Paper 80-1A:329-333.

______. 1982a. Vegetation of the Cornwallis, Little Cornwallis and associated islands, District of Franklin. Geological Survey of Canada Open File Map 857.

______. 1982b. Vegetation of Melville Island, District of Franklin: Eastern Melville Island and Dundas Peninsula. Geological Survey of Canada Open File Map 852.

______. 1983a. Bioclimatic zonation in a High Arctic region: central Queen Elizabeth Islands. In: Current Research, Part A, Geological Survey of Canada, Paper 83-1A:381-390.

______. 1983b. Reconnaissance vegetation studies on western Victoria Island, Canadian Arctic Archipelago. In: Current Research, Part B, Geological Survey of Canada, Paper 83-1B:75-81.

______. 1983c. Vegetation of the Bathurst Island area, Northwest Territories. Geological Survey of Canada Open File Map 888.

______. 1983d. Vegetation of the north-central Queen Elizabeth Islands, District of Franklin, N.W.T. Geological Survey of Canada Open File Map 887.

______. 1985. Lichen-free zones as neoglacial indicators on western Melville Island, District of Franklin. In: Current Research, Part A, Geological Survey of Canada, Paper 85-1A:709-712.

______. 1986a. Modern arctic vegetation distribution and its congruence with summer climate patterns. In: French, H.M., ed. Proceedings, Impact of Climatic Change on the Canadian Arctic, Orillia, Ontario, March 3-5, 1986. Downsview, Ontario: Atmospheric Environment Service, Environment Canada. 84-99.

______. 1986b. Vegetation-geology-climate relationships of western Melville Island, District of Franklin. In: Current Research, Part A, Geological Survey of Canada, Paper 86-1A:719-726.

______. 1987a. Plants: living weather stations. Geos 16(2):9-13.

______. 1987b. Vegetation of Melville Island, District of Franklin, Northwest Territories: western Melville Island. Geological Survey of Canada Open File Map 1509.

______. In press. The distribution of plant communities on Melville Island, Northwest Territories. In: Christie, R.L., ed. Geological Reports, Melville Island. Geological Survey of Canada Paper.

ENERGY MINES AND RESOURCES. 1973. Vegetation Regions. In: National Atlas of Canada. Ottawa: Queen's Printer. 45-46.

ENGLAND, J., KERSHAW, L., LAFARGE-ENGLAND, C., and BEDNARSKI, J. 1981. Northern Ellesmere Island, a natural resource inventory. Report submitted to Parks Canada, Environment Canada, Ottawa. Ms. 236 p.

FOSCOLOS, A.E., and KODAMA, H. 1981. Mineralogy and chemistry of Arctic Desert soils on Ellef Ringnes Island, Arctic Canada. American Journal of Soil Science 45(5):987-993.

FREEDMAN, B., SVOBODA, J., LABINE, C., MUC, M., HENRY, C., NAMS, M., STEWART, J., and WOODLEY, E. 1983. Physical and ecological characteristics of Alexandra Fiord, a High Arctic oasis on Ellesmere Island, Canada. In: Proceedings, 4th International Conference on Permafrost, Fairbanks, Alaska. 301-306.

GOULD, J. 1985. Plant Communities of the Lake Hazen area, Ellesmere Island, N.W.T. Master's thesis, Department of Botany, University of Toronto, Erindale Campus, Mississauga, Ontario. 325 p.

HARDY, R.M., and ASSOCIATES LTD. 1977. Landscape Survey, District of Franklin, N.W.T. 1976. (Edited by O.A. Steen.) Report prepared for Polar Gas Project, Environmental Program. 223 p. Available at Hardy, B.B.T. Ltd., 219 18th Street S.E., Calgary, Alberta T2E 6J5.

HARE, F.K. 1968. The Arctic. Quarterly Journal of the Royal Meteorological Society 94(402):439-459.

______. 1970. The Tundra Climate. Transactions of the Royal Society of Canada, Series IV, 8:393-399.

HENRY, G., FREEDMAN, B., and SVOBODA, J. 1986. Survey of vegetated areas and muskox populations in east-central Ellesmere Island. Arctic 39(1):78-81.

HODGSON, D.A., co-ord. In press. Quaternary geology of the Queen Elizabeth Islands. Chapter 6. In: Fulton, R.J., Heginbottom, J.A., and Funder, S., eds. Quaternary Geology of Canada and Greenland. Geology of Canada No. 1. Geological Survey of Canada. (Also being published by Geological Society of America: Geology of North America K-1.)

______ and EDLUND, S.A. 1975. Surficial materials and biophysical regions, eastern Queen Elizabeth Islands. Part 1: Maps and legend for Baumann Fiord and Graham Islands. Geological Survey of Canada Open File 265.

______. 1977. Biophysical regions, western Fosheim Peninsula and eastern Axel Heiberg Island. Geological Survey of Canada Open File 501.

______. 1978. Surficial materials and vegetation, Amund Ringnes and Cornwallis islands, District of Franklin. Geological Survey of Canada Open File 541.

HODGSON, D.A., and VINCENT, J-S. 1984. A 10 000 yr B.P. extensive ice shelf over Viscount Melville Sound, Arctic Canada. Quaternary Research 22:18-30.

HOLDRIDGE, L.R. 1947. Determination of world plant formations from simple climatic data. Science 105(2727):367-368.

______. 1966. The life zone system. Adsonia 6:199-203.

HOLMGREN, B. 1971. Climate and energy exchange on a subpolar ice cap in summer. Part F: on the energy exchange of the snow surface at Ice Cap Station. Arctic Institute of North America, Devon Island Expedition 1961-1963. Uppsala, Sweden: Meteorologiska Institutionen. 53 p.

HOOKER, J.D. 1857. On some collections of Arctic Plants, chiefly made by Dr. Lyall, Dr. Anderson, Herr Miertsching, and Mr. Rae, during the Expeditions in search of Sir John Franklin, under Sir John Richardson, Sir Edward Belcher, and Sir Robert McClure. Journal of the Proceedings of the Linnaean Society 1:114-124.

HUSTICH, I. 1983. Treeline and tree growth studies during 50 years: some subjective observations. In: Morisset, P., and Payette, S., eds. Tree-line Ecology; Proceedings of the Northern Quebec Tree-line Conference. Collection Nordicana No. 47; Université Laval, Québec. 181-188.

JACKSON, C.I. 1959. Coastal and inland weather contrasts in the Canadian Arctic. Journal of Geophysical Research 64(10):1451-1455.

______. 1969. The summer climate of Tanquary Fiord, N.W.T., a five year review. Defense Research Board, Publication in Meteorology no. 95. 65 p.

KAUPPI, P., and POSCH, M. 1985. Sensitivity of boreal forests to possible climatic warming. Climate Change 7(1):45-54.

KING, R.L. 1981. Das Sommerklima von N-Ellesmere Island, N.W.T. Kanada — Eine Beurteilung von Stationswerten unter besonderer Berücksichtigung des Sommers 1978. Heidelberger Geographische Arbeiten, Heft 69:77-107.

KOERNER, R.M. 1979. Accumulation, ablation and oxygen isotope variations on the Queen Elizabeth Islands ice caps, Canada. Journal of Glaciology 22:25-41.

KÖPPEN, W. 1923. Die Klimate der Erde: Grundriss der Klimakunde. Berlin: Walter de Gruyter. (Summarized, in 1937, by the Committee of the Geographical Association.) In: Geography 22(4):253-282.

KUC, M. 1970. Vascular plants from some localities in the western and northern parts of the Canadian Arctic Archipelago. Canadian Journal of Botany 48(11):1931-1938.

LARSEN, J.A. 1971. Vegetational relationships with air mass frequencies: boreal forest and tundra. Arctic 24(3):177-194.

______. 1974. Ecology of the northern continental forest border. In: Ives, J.D., and Barry, R.G., eds. Arctic and Alpine Environments. London: Methuen. 341-369.

______. 1980. The Boreal Ecosystem. New York: Academic Press. 127 p.

LOTZ, J.R., and SAGAR, R.B. 1962. Northern Ellesmere Island, an arctic desert. Geografiska Annaler XLIV(3-4):366-377.

MAUSBACHER, R. 1981. Gefässpflanzen von Oobloyah Bay, N-Ellesmere Island, N.W.T., Kanada; eine Kommentierte Pflanzen liste und phänologische Beobachtungen. In: Barsch, D., and King., L. eds. Ergebnisse der Heidelberg Ellesmere Island Expedition. Heidelberger Geographische Arbeiten Heft 69:541-553.

MAXWELL, J.B. 1980. The climate of the Canadian Arctic Islands and adjacent waters. Vol. I. Environment Canada Climatological Studies No. 30. 532 p.

______. 1981. Climatic regions of the Canadian Arctic Islands. Arctic 34(3):225-240.

______. 1982. The climate of the Canadian Arctic Islands and adjacent waters. Vol. II. Environment Canada Climatological Studies No. 30. 589 p.

MÜLLER, F., BLATTER, H., BRAITHWAITE, R., ITO, H., KAPPENBERGER, G., OHMURA, A., SCHROFF, K., and ZUST, A. 1976. Report on North Water Project Activities 1 October 1974 to 30 September 1975. Progress report, McGill University and Swiss Federal Institute of Technology. Unpubl. ms. 149 p. Available at the Department of Geography, McGill University, Montreal, Quebec.

NORDENSKJÖLD, O., and MECKING, L. 1928. The Geography of Polar Regions. American Geographical Society Special Publication No. 8. 359 p.

OHMURA, A. 1981. Climate and energy balance on arctic tundra: Axel Heiberg Island, Canadian Arctic Archipelago Spring and Summer 1969, 1970, and 1972. Zürcher Geographische Schriften. Eidgenüssiche Technische Hochschule Zurich, Heft 3. 448 p.

ORVIG, S., ed. 1970. Climates of the Polar Regions. World Survey of Climatology. Vol. 14. Amsterdam: Elsevier. 370 p.

PARKER, G.R. 1977. The flowering phenology of common vascular plants at Bailey Point, Melville Island, Northwest Territories. Canadian Field-Naturalist 91:81-83.

______. 1978. The diets of muskoxen and Peary caribou on some islands in the Canadian High Arctic. Canadian Wildlife Service Occasional Paper No. 35. 19 p.

______ and ROSS, R.K. 1976. Summer habitat use by muskoxen (*Ovibos moschatus*) and Peary caribou (*Rangifer tarandus Pearyi*) in the Canadian High Arctic. Polarforshung 1:12-25.

POLUNIN, N. 1940a. The flora of Devon Island in arctic Canada. Canadian Field-Naturalist 54:31-37.

______. 1940b. Botany of the Canadian Eastern Arctic, Part 1: Pteridophyta and spermatophyta. National Museums of Canada Bulletin No. 92. 408 p.

______. 1948. Botany of the Canadian Eastern Arctic Part III: Vegetation and Ecology. National Museums of Canada Bulletin 104. 304 p.

______. 1951. The real Arctic: suggestions for its delimitation, subdivision and characterization. Journal of Ecology 39:308-315.

______. 1960. Introduction to Plant Geography and Some Related Sciences. New York: McGraw-Hill. 640 p.

PORSILD, A.E. 1964. Illustrated Flora of the Canadian Arctic Archipelago. National Museums of Canada Bulletin 146. 218 p.

______ and CODY, W.J. 1980. Vascular Plants of the Northwest Territories, Canada. Ottawa: National Museums of Canada. 667 p.

POWELL, J.M. 1961. The vegetation and micro-climate of the Lake Hazen area, northern Ellesmere Island, N.W.T. McGill University, Arctic Meteorology Research Group, Publication in Meteorology 38. 112 p.

RANNIE, W.F. 1986. Summer air temperature and number of vascular species in Arctic Canada. Arctic 39(2):133-137.

SAVILE, D.B.O. 1961. The botany of the northwestern Queen Elizabeth Islands. Canadian Journal of Botany 39:909-942.

______. 1964. General ecology and vascular plants of the Hazen Camp area. Arctic 17(4):237-258.

______. 1971. Microclimate and plant growth at Isachsen and Mould Bay. Arctic 24:306-307.

SCHOFIELD, W.B., and CODY, W.J. 1955. Botanical investigations on southern Cornwallis Island, Franklin District, N.W.T. Canadian Field-Naturalist 69:116-128.

SHEARD, J., and GEALE, D.W. 1983a. Vegetation studies at Polar Bear Pass, Bathurst Island, N.W.T., I: Classification of plant communities. Canadian Journal of Botany 61:1618-1636.

______. 1983b. Vegetation studies at Polar Bear Pass, Bathurst Island, N.W.T., II: Vegetation-environment relationships. Canadian Journal of Botany 61:1637-1646.

SIM, V.K. 1957. Geographical aspects of weather and climate at Eureka, Northwest Territories. Geographical Bulletin 10:36-53.

SIMMONS, H.G. 1906. The vascular plants in the flora of Ellesmere land. In: Second Norwegian Expedition in the "Fram" 1898-1902. 1(2):1-197.

______. 1913. A survey of the phytogeography of the Arctic American Archipelago, with some notes about its exploration. Lund, Sweden: Lunds Universitets Arsskrift Ny Foljd, Avdelningen 2, Band 9, Number 19. 183 p.

SINGH, T., and POWELL, J.M. 1986. Climatic variation and trends in the boreal forest region of western Canada. Climatic Change 8(3):267-278.

SOPER, J.H., and POWELL, J.M. 1983. Botanical studies in the Lake Hazen Region, northern Ellesmere Island, Northwest Territories, Canada. National Museums of Canada, Publications in Natural Sciences No. 5. 67 p.

SVOBODA, J., and FREEDMAN, B., eds. 1981. Ecology of a High Arctic Lowland Oasis, Alexandra Fiord (78°53'N; 75°55'W), Ellesmere Island, N.W.T., Canada. Progress Report of Alexandra Fiord Lowland Ecosystem Study. Toronto and Halifax: University of Toronto and Dalhousie University. 245 p.

TARNOCAI, C. 1976. Soils of Bathurst, Cornwallis and adjacent islands, District of Franklin. In: Current Research, Part B, Geological Survey of Canada, Paper 76-1B:137-141.

THORSTEINSSON, R. 1958. Cornwallis and Little Cornwallis Islands, District of Franklin, Northwest Territories. Geological Survey of Canada Memoir 294. 134 p.

TOZER, E.T., and THORSTEINSSON, R. 1964. Western Queen Elizabeth Islands, Arctic Archipelago. Geological Survey of Canada Memoir 332. 242 p.

TRANQUILINI, W. 1979. Physiological Ecology of the Alpine Timberline. New York: Springer-Verlag. 131 p.

TUHKANEN, S. 1984. A circumboreal system of climatic-phytogeographical regions. Acta Botanica Fennica 107:1-50.

VINCENT, J-S., and EDLUND, S.A. 1978. Surficial Geology, Banks Island, Northwest Territories. Geological Survey of Canada Open File 577.

VOWINCKEL, E., and ORVIG, S. 1970. The Climate of the North Polar Basin, Chapter 3. In: Orvig, S., ed. World Survey of Climatology. Vol. 14. Amsterdam: Elsevier. 129-252.

WATERSTON, G., and WATERSTON, I. 1972. Report on wildlife, vegetation and environmental values in the Queen Elizabeth Islands: Ellesmere and part of Axel Heiberg Island, June 28-August 15, 1972. Ottawa: Canadian Wildlife Service. Report CWSC 1481. 54 p.

WEIN, R.W., and RENCZ, A.N. 1976. Plant cover and standing crop sampling procedures for the Canadian High Arctic. Arctic and Alpine Research 8(2):139-150.

WOO, M-K., HERON, R., MARSH, P., and STEER, P. 1983. Comparisons of weather station snowfall with winter snow accumulation in High Arctic basins. Atmosphere-Ocean 21(3):312-325.

YOUNG, S.B. 1971. Vascular flora of St. Lawrence Island, with special reference to floristic zonation in the arctic regions. Contributions from the Gray Herbarium of Harvard University No. 201:11-115.

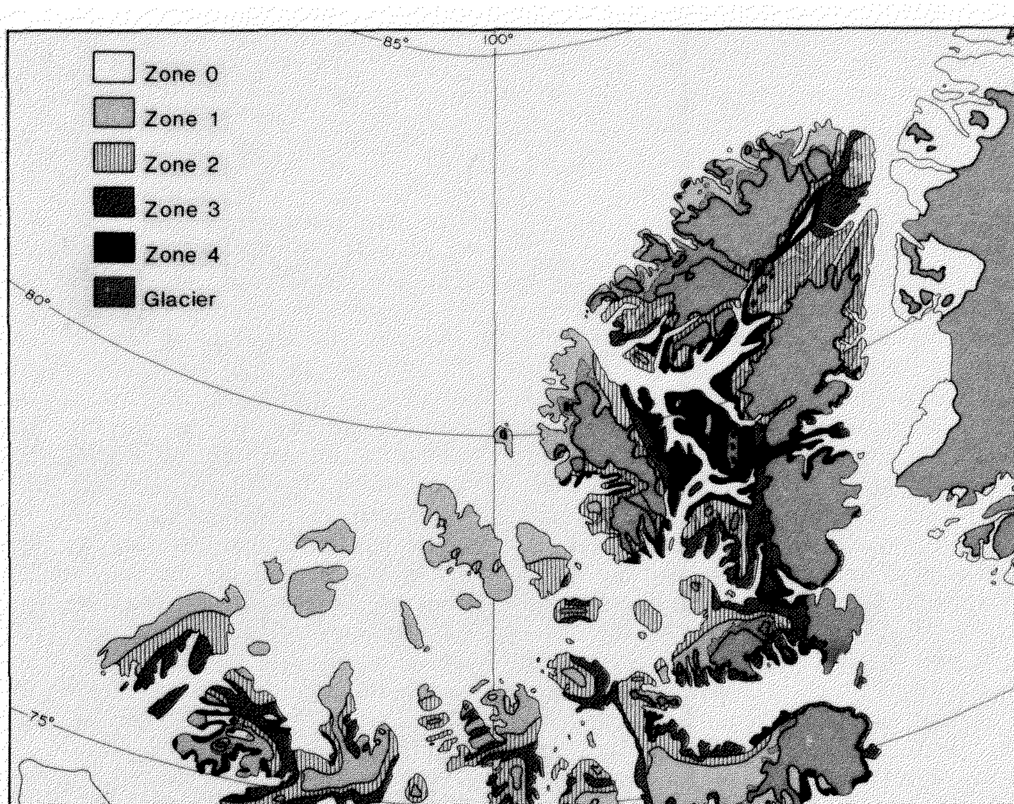

FIG. 5.

ERRATUM: *Regional Congruence of Vegetation and Summer Climate Patterns in the Queen Elizabeth Islands, Northwest Territories, Canada,* by Sylvia A. Edlund and Bea Taylor Alt, *Arctic*, Vol. 42, No. 1 (March 1989):10 — the zones in Figure 5 are more clearly printed below.

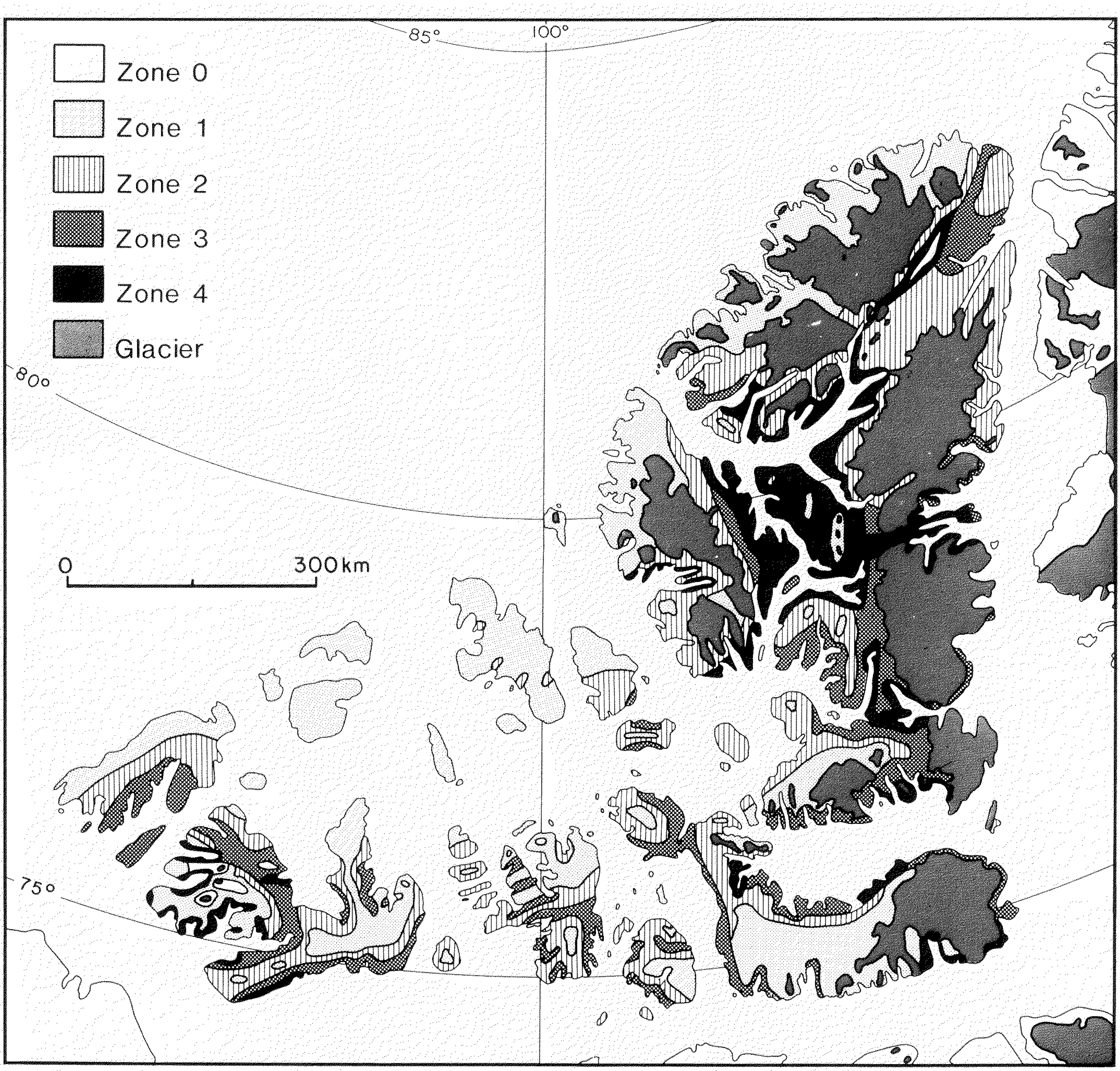

FIG. 5. Vegetation zones of the Queen Elizabeth Island based on the growth forms of the dominant vascular plant species. The zones are summaries of patterns seen on 1:250 000 scale vegetation maps (Edlund, 1982a,b, 1983c,d, 1987b).